TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Wirtschaftswissenschaften

DRESDNER BEITRÄGE ZUR LEHRE DER BETRIEBLICHEN UMWELTÖKONOMIE

Nr. 58/2012

Günther, E. / Scheel, R. (Hrsg.)

Comparative LCA of Wood from conventional Forestry and Wood from Short Rotation Coppice

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Herausgeber:

Lehrstuhl für
Betriebswirtschaftslehre
Betriebliche Umweltökonomie

ISSN 1611-9185

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Diplomarbeit eingereicht: 2012
Veröffentlicht: 2012

Foreword

Due to the emergence of shortages concerning natural resources and the globalization of production, sustainability has become vital in business decisions. Meanwhile, sustainability management has become an independent field of research in business science and in the decision processes of companies. The research and teaching of the Chair of Environmental Management and Accounting of the Technische Universität Dresden focus on the economic and environmental efficiency (e^3) in organizations. Strategies for practical use are developed based on scientific concepts. In recent years the importance of the natural environment in the economic sciences has been increasing continuously.

The research program of the Chair of Environmental Management and Accounting at the Technische Universität Dresden is reflected in the composition of the teachings. In this way the knowledge gained from the theoretical and practical research flows directly into each of the lectures. The current scientific series "Dresdner Beiträge zur Lehre der Betrieblichen Umweltökonomie" aims to support this integration process. Contents of the scientific series are predominantly theses selected from the Chair of Environmental Management and Accounting through which the reader may gain an insight into the key activities of the chair as well as a clear understanding of the work content.

The scientific series was composed by Dr. Susann Silbermann and the coordination of the present series was carried out by Dipl.-Kffr. Kristin Stechemesser.

Worldwide there is an increasing demand of natural resources. In future, non renewable resources get substituted by renewable resources in the energetic sector as well as in the material sector. That implies a stronger usage of renewable resources especially - wood. In 2009 there was a usage of 77 million cubic meters of wood for material applications and a quantity of 55 million cubic meters for energetic applications in Germany alone. Furthermore, there is an increasing demand on wood for energetic purposes. In 2007 this problematic development led to the first supply bottlenecks. To meet the increasing demands of the future, Short Rotation Coppices (SRC) can help to improve the wood provision.

An SRC is a planting of fast growing coppice on agricultural areas, which is managed more intensively than usual forestry practices for a quicker production of wooden biomass. With a comparative LCA of conventional wood and wood from SRC the present study evaluates if wood from SRC is reasonable to cover the increasing demand of wood for material and energetic purposes in an environmental friendly way. A comprehensive literature research regarding LCAs of wood and wooden products shows that there are no previous studies comparing the two types of wood. Hence, the present study examines a particleboard production as the material scenario and the combustion of woodchips in a firing system as the energetic scenario to compare the ecological advantages and disadvantages of wood from SRC and conventional wood. The LCA is implemented with the Gabi software designed by PE International. Data is obtained from previous LCA studies evaluating the production of wood, the particleboard production and the combustion of wood.

Additionally, data from the Ecoinvent database is used. Functional units are the production of 1m3 particleboard and the production of 1 MJ of thermal energy. The LCIA is implemented with the "Ecoindicator" as endpoint- and "CML 2001" as midpoint approach to cover broad range of environmental issues. Moreover a sensitivity analyses shows the impact of decisive variables on the results of “Ecoindicator” and “CML 2001”.

Results reveal that outcomes of the LCIA are dependent of the assessment method and the processed part of trees from conventional forestry. The present study shows, that with an efficient land use, wood from SRC can help to cover the increasing demand of wood for material and energetic purposes in a sustainable way. However, an immediate usage of wood for energetic purposes has to be seen critical. Instead, a cascaded and sustainable utilization of wood is recommendable to counteract climate change and to improve the efficient use of the renewable resource - “wood”.

Edeltraud Günther

The scientific foundation of the work is based upon the results of the diploma thesis by Martin Kunstmann which was written at the TU Dresden, Chair of Environmental Management and Accounting.
Professor/Lecturer: Prof. Dr. Edeltraud Günther / Supervisor: Dipl.-Vw. Ramona Scheel. The author is solely responsible for the content of this scientific work.

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List of Abbreviations

a	per year
ADP f.	Abiotic depletion for fossil resources
AP	Acidification potential
bd	bone dry (atro)
BS	board shaping subsystem
BF	board finishing subsystem
ghg	greenhouse gas
CO_2	carbon dioxide
DALY	Disability Adjusted Life Years
e.g.	for example
eds.	Editor
EN	European standard
EP	Eutrophication potential
etc.	et cetera
et seq.	following
EQ	Damage to ecosystem quality
fm	solid cubic meter
GWP	Global Warming Potential
ha	hectars
HH	Damage to human health
ISO	International Organization for Standardization
kg	kilograms
km	kilometers
kWh	kilowatt-hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^2	square meter
MJ	megajoule
MPa	megapascal
MW	megawatts
NO_x	nitrogen oxides
ORC	Organic Rankine Cycle
p.	page

PDF	potentially disappeared fraction
POCP	Photo-oxidant creation potential
R	Damage to resources
SRC	Short Rotation Coppice
Srm	stere
tkm	tonne kilometer
t	tonne
UF	urea - formaldehyde
w. p.	without page
yr	Year

1 Introduction

Forestry plays an important role for the life of human beings. The forest is not only a place of recovery and habitat of flora and fauna; furthermore, it is a filter for air and water, an essential climate-regulator and one of the most important providers of raw material.

The supply of energy and resources, the preservation of our natural environment, biodiversity as wells as climate change are central challenges of our time. These issues are strongly linked to forestry. There is no question that there are increasing demands on forest- and wood economy: A sustainable forest management influences climate change positively. The forest is an enormous CO_2 sink. On the other side climate change has direct impact on the development of forestry. Furthermore there are increasing demands due to a changing leisure behavior, a stronger consciousness of environmental protection together with an increasing consumption of wood for energetic and material purposes. Worldwide there are increasing demands for natural resources. In future, non-renewable resources shall be substituted by renewable resources in the energetic sector as well as in the material sector. That implies a stronger usage of renewable resources especially - wood.[1]

Beside agribusiness, forestry is the most significant source of raw material for biomass. Over the last two decades there has been a continuously increasing consumption of forest based raw materials. In 2009 there was a usage of 77 million cubic meters of wood for material applications and a quantity of 55 million cubic meters for energetic applications in Germany alone. In addition to the industrial- and construction sectors the pulp industry has an increasing demand of wood as well. Furthermore, there is an increasing demand on wood for energy production in Germany through the German Renewable Energy Sources Act. In 2007 this problematic development led to the first supply bottlenecks. Today, about 10 percent of the worldwide primary energy demand is satisfied by wood. Especially due to escalating prices for non-renewable resources the utilization of wood for energy and heat production has increased rapidly. Thus, it is uncertain how long the demand for wood can be satisfied. Therefore, the goals of a sustainable forestry are: sustainable wood harvesting, the establishment of a reasonable cascade utilization, increasing resource efficiency of the material- and energetic sector and the avoidance of rivalry between energetic- and material usage of wood.[2]

One problem-solving approach can be the establishment of Short Rotation Coppices (SRC). They can help to improve the wood provision. There are currently approximately 3000 ha of SRC are cultivated in Germany; which is a rather limited scale of cultivation.[3] By means of an Life Cycle Assessment (LCA) it can be analyzed, if SRC are also ecologically reasonable. LCA is an important instrument concerning the documentation of environmental impacts of our economical acting. LCAs for wood and all kinds of wood products show the unique role of wood in a sustainable economy. Hence, an LCA of conventional wood and wood from SRC can clarify if wood from SRC can help to cover the increasing demand of wood for material and energetic purposes in an environmental friendly way. The present study is implemented to

[1] Cf. BMELV (eds.) (2004), p. 9 et seq.
[2] Cf. BMELV (eds.) (2009), p. 5 et seq.
[3] Cf. BMELV (eds.) (2009), p. 8 et seq.

evaluate ecological advantages and disadvantages of using wood from SRC and conventional forestry from a comparative perspective.

Figure 1 shows the structure of the study.

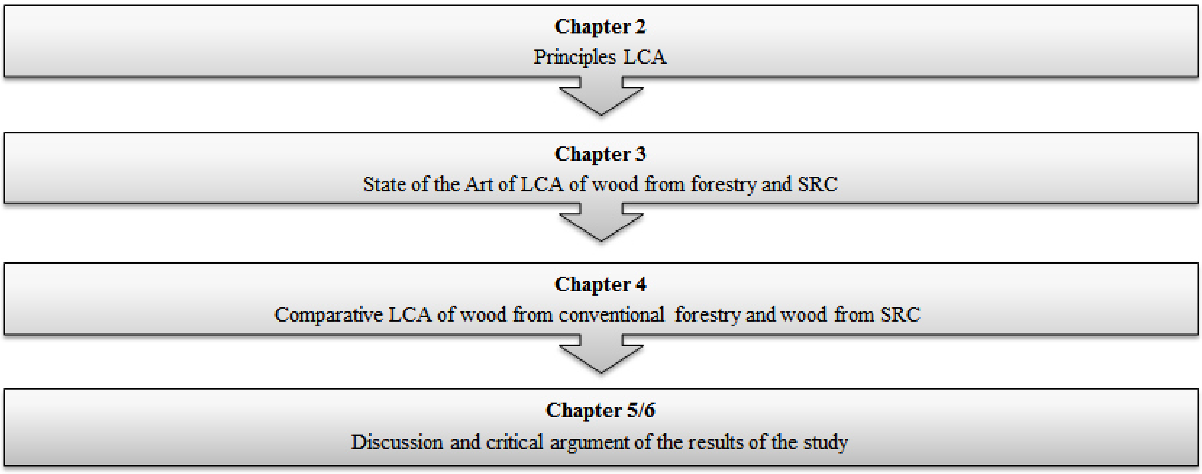

Figure 1: Structure of the study
(Own illustration.)

In order to understand the function and goals of an LCA, the next chapter describes the methodology of an LCA study as well as the challenges for comparative LCAs. Chapter 3 gives a detailed overview over previous LCA studies of wood products from conventional forestry and SRC. The final section of chapter 3 describes relevant LCA studies which are necessary to compare the two wood types in detail. Eventually, the research questions are derived from the insights of the literature review. The comparative LCA of wood from conventional forestry and SRC is implemented in chapter 4. Thereby, the insights from the literature review are used. Especially ecological aspects regarding material and energetic use of wood from both sources are analyzed. Considering two scenarios, the manufacturing of a wooden product and bioenergy from wood will be analyzed from an environmental point of view. Thereby the most ecological scenario for the production of both products will be identified. Finally, a sensitivity analysis is implemented in order to discuss the variation of parameters. Chapter 5 and 6 discuss and reflect the results of the study critically.

2 Principles of Life Cycle Assessment

This chapter describes the method of LCA. First, LCA in general is treated. Furthermore, the specific phases "Goal and Scope Definition", "Life Cycle Inventory" (LCI), "Life Cycle Impact Assessment" (LCIA) and "Interpretation" are considered more precisely. Moreover, uncertainties in LCA and challenges for comparative LCAs are considered.

2.1 Methodology of Life Cycle Assessment

The International Organization for Standardization (ISO) standard describes LCA as an approach that considers the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal.[4] LCA addresses the environmental aspects and impacts of a product system. It is a relative approach, which is structured around a functional unit with an iterative technique: The individual phases of an LCA use results of the other phases. Thereby transparency and comprehensiveness are important guiding principles to ensure a proper interpretation of the results.

LCA studies comprise four phases, which are illustrated in Figure 2: Goal and Scope Definition, LCI, LCIA and Interpretation.[5]

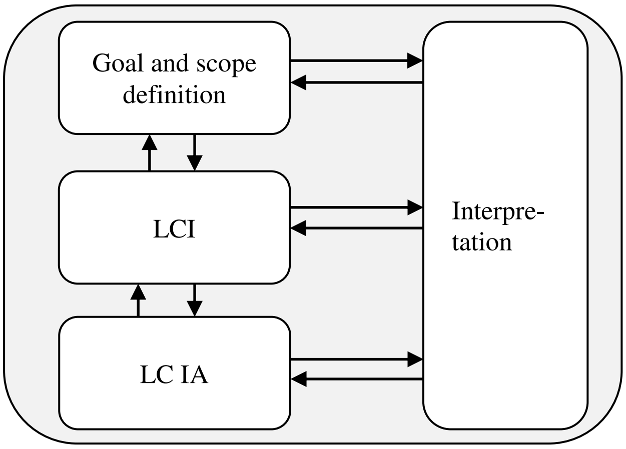

Figure 2: Life Cycle Assessment Framework
(Source: modified after DEUTSCHES INSTITUT FÜR NORMUNG E.V. (Eds.) (2006a), p. 16)

The Goal and Scope Definition is of high importance. Beside the reason of implementation, the goal, the depth and the system to be analyzed are described, supplemented with the following aspects:

- System boundaries
- Functional unit
- Data and data quality
- Assumption
- Kind of impact assessment

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[4] Cf. PENNINGTON, D.W. et al. (2004), S. 721.
[5] Cf. DEUTSCHES INSTITUT FÜR NORMUNG E.V. (Eds.) (2006), p. 2.

- Groups to be addressed[6]

An important part of the goal and scope definition is the functional unit. The consideration of a functional unit allows comparing and analyzing goods or services.[7]

The LCI is the central component of LCA. All activities related to the production of one functional unit have to be analyzed concerning the following components:

- Raw material extraction
- Intermediate products
- Product or service itself
- Energy, transportation, auxiliary products
- Outputs (byproducts, emissions to air- water and soil, solid wastes)

The inventory analysis contains the following steps: data collection, data calculation and the allocation of flows and releases; with the result of an inventory table containing a list of all inputs and outputs per functional unit.[8]

The LCIA has to be implemented for a deeper understanding of the systems investigated and for a comparative assessment of product systems. It provides indicators for analyzing the potential contributions of the resource extractions and wastes/emissions in an inventory to a number of potential impacts.[9] There are different life cycle impact assessment methods. However, the general framework of an assessment method composes of the following several elements:

- Classification: Building of impact categories with the help of a grouping of the data from inventory analyses.
- Characterization: Aggregation of impacts within categories.
- Normalization: The category indicator results are compared using a reference value (e.g. number of inhabitants, reference region).[10] After normalization a comparison of the environmental impacts across the impact categories is possible. It further helps to better understand the relative importance and magnitude of the category results.[11] Despite of normalization makes it possible to translate abstract impact scores into a relative contribution of the product to a reference situation, normalizations have to be seen critical as they are often calculated under great uncertainty. This problematic issue can be seen in study of SLEEWIJK, A. W. et al. (2008), where normalization for different impact categories is computed with the help of diverse estimations, assumptions and uncertainties.[12]
- Weighting is an optional element of the LCA that is based on value-choices rather than scientific principles. Weighting is used to compare different impact indicator results according to their significance.[13]

6 Cf. KLOEPFFER, W. (1997), p. 224.
7 Cf. REBITZER, G. et al. (2004), p. 704.
8 Cf. REBITZER, G. et al. (2004), p. 704.
9 Cf. REBITZER, G. et al. (2004), p. 704.
10 Cf. BOVEA, M. D.; GALLARDO, A. (2006), p. 210.
11 Cf. ROEDL, A. (2010), p. 571.
12 Cf. SLEEWIJK, A. W. et al. (2008), p. 236 et seq.
13 Cf. BOVEA, M.D.; GALLARDO, A. (2006), p. 210.

The result of LCIA is an evaluation of a product life cycle or parts of a product life cycle, on a functional unit basis, in terms of a midpoint- (problem-) - or endpoint- (damage-) oriented approach.[14] As illustrated in Figure 3 midpoints are considered to be a point in the cause-effect chain[15] of a particular impact category, between inventory data and prior to the endpoint. Endpoint-based approaches assessing human health, resource and ecosystem impacts at the endpoint in a cause-effect chain, which occur as a result of categories traditionally addressed using midpoint category indicators.[16] E.g.: inventory data is classified and characterized to ghg (greenhouse gas) emissions which affect the midpoint impact category "Global Warming Potential". If a midpoint oriented approach is chosen, the assessment stops at this point, which is often critical for the interpretation phase of LCA, because it is difficult to evaluate the relevance of a midpoint impact category to specific situations such as human health. Thus, the endpoint approach goes one step further: Beside the steps described above, category indicators are formed for specific environmental issues. Within a next step, damages of these indicators to human health, ecosystem quality and resources are calculated. Finally, a weighting of these three damage categories is implemented.[17] Hence, the reader of an LCA doesn't have to interpret the relevance of a midpoint category such as acidification, and understands the impact, e.g., to human health more easily.

Despite the benefit of understandable results, there are great uncertainties concerning data and correctness of the model. Due to a high quantity of assumptions, estimations or even gaps in knowledge's regarding the consequences of category indicators to human health, ecosystem quality and resources, results of an endpoint approach have to be seen critical.[18]

There is a lively discussion regarding mid- or endpoint modeling with the tendency towards endpoint modeling:[19] Like described above, endpoint oriented approaches are more understandable to decision makers, as there is no need to deal separately with the environmental relevance of the category indicators, because they are chosen at an endpoint level. Moreover, they enable an easier evaluation of the magnitude of effects and additionally increase the understanding of the environmental mechanism. This is advantageous due to many decision makers inability to abstract midpoints. Another advantage of endpoint modeling accrues through common entities of the characterization categories such as DALY: with this e.g. human health impacts associated with climate change can be compared with those of ozone depletion. Due to the necessity of several conditions, such as a high level of knowledge, data quality and expert involvement which is also necessary to forecast specific endpoints effects, some authors are critical of endpoint modeling and recommend the midpoint approach. In their opinion the availability of reliable data and sufficiently robust models remains to limited to support endpoint modeling. Moreover, an extension to endpoint modeling is based on a number of additional assumptions and value choices, which do not necessarily reflect the viewpoint of other experts or users; additionally they might not be transparent to them. Due to high uncertainties and additional complexity, endpoint modeling will only be warranted if it

[14] Cf. REBITZER, G. et al. (2004), p. 704.
[15] Cf. PENNINGTON, D. W. et al. (2004), p. 726 et seq.
[16] Cf. BARE, J. et al. et al. (2000), p. 319.
[17] Cf. GOEDKOOP, M. et al. (2000), p. 2 et seq.
[18] Cf. BARE, J. et al. (2000), p. 320 et seq.
[19] Cf. GOEDKOOP, M. et al. (2000), p. 17.

provides an improvement in the decision making process. Furthermore, some measures cannot be quantified at the endpoint level, e.g. biodiversity. Generally, endpoint models focus on a smaller number of pathways compared with midpoint models which are more comprehensive due to their relevance for a wider variety of impacts at endpoint level. However, there is a trade-off between midpoint analysis where things are known with more certainty and endpoint analysis where things are known with more relevance. Indicators at midpoint level may be preferred for specific communication purposes e.g. global warming but indicators at endpoint level lead to more understandable results. There are advantages and disadvantages to each approach. Thus, it is suggested to use both approaches together to provide more information.[20] However, there is a need for consistent system that can provide data at both levels.

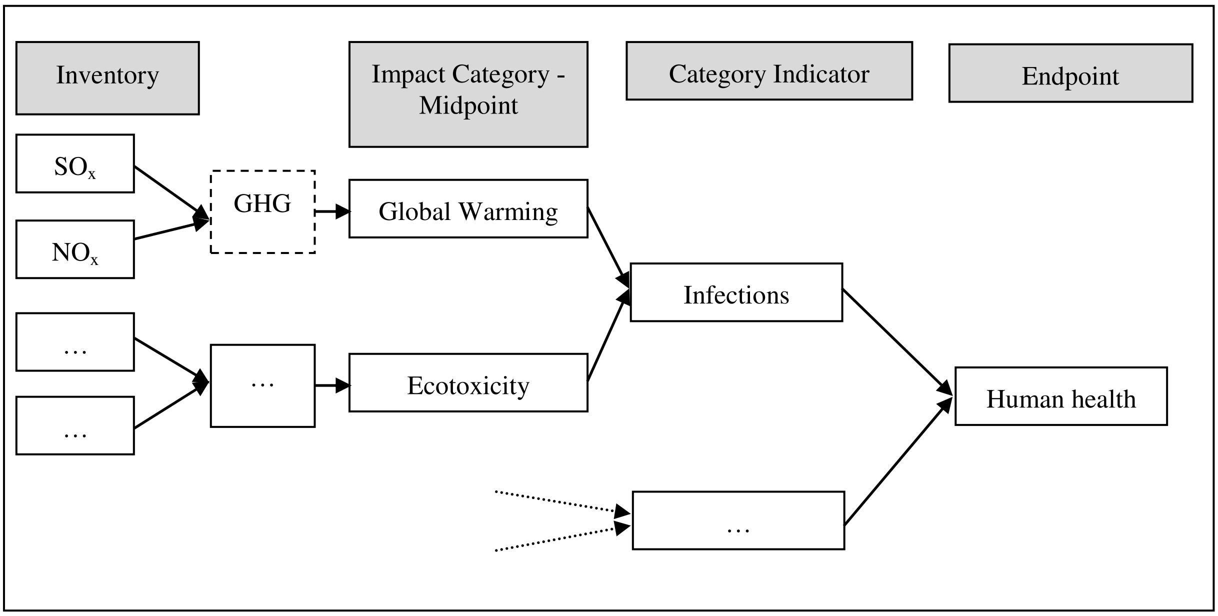

Figure 3: Simplified framework of mid- and endpoint assessment structure
(Source: modified after PENNINGTON, D.W. et al. (2003), p. 723.)

The Interpretation Phase is an evaluation of the analysis, assumptions, and choices of the study. Main elements of this phase are a critical evaluation (in terms of consistency and completeness) and analysis (for instance, in terms of robustness) of results and the formulation of the conclusions and recommendations of the LCA study.[21]

2.2 Uncertainty in LCA

Uncertainty is an important aspect for LCA. Uncertainties can strongly influence the outcomes of an LCA study. E.g. for a comparative study it is important to know if results of the more environmentally friendly product are robust or significant. The problem is, that information is often scattered and terminology not standardized. There are two questions arising: What are the aspects of uncertainty in relation to LCA and what are the practical approaches to address these uncertainties? HEIJUNGS, R.; HUIJBREGTS, M.A.J. (2004) describe uncertainty in terms of data for which: no value, an inappropriate value or more than one value is

[20] Cf. BARE, J. et al. (2000), p. 319 et seq.
[21] Cf. GUINEE, J. et al. (2001), p. 81.

available. Uncertainty has to be distinguished from variability, which is a quality of data of a heterogeneous nature. However, approaches of the two issues strongly overlap and are therefore not differentiated in the present study. There are many approaches classifying uncertainty. First approaches distinguished between data-, model- and completeness uncertainty; later approaches added issues such as parameter uncertainty or spatial and temporal variability. A detailed overview is given in HEIJUNGS, R.; HUIJBREGTS, M.A.J. (2004). There are four approaches addressing uncertainty: the scientific ("Doing more research"), the constructivist ("Involving stakeholders"), the legal ("Relying on authoritative bodies such as ISO") and the statistical approach ("Using statistical methods").[22] For the scientific approach, data and data quality are important issues:

The data used in an LCI is the backbone of the assessment. The reliability of the results of LCA depends on them heavily. A "data quality management" is therefore most reasonable. One method for data quality management is the usage of the five data quality indicators "Reliability-", "Completeness-", "Temporal-", "Geographical-" and "Technological Indicator" of WEIDEMA, B.P.; WESNAES M.S. (1996) summarized in the so-called pedigree matrix.[23] The matrix is attached in Appendix VII. The statistical approach contains different methods. HEIJUNGS, R.; HUIJBREGTS, M.A.J. (2004) classify them as follows: parameter variations, sampling-, analytical- and non-traditional methods. One parameter variation method is the sensitivity analysis. For this analysis one parameter is changed systematically while the other parameters are kept steadily. This method can be repeated for the critical parameters to show parameters with strong influence on the result. As a consequence potential improvement can be discussed.[24] As it can be seen in the overview of BJOERKLUND, A.E. (2002), which is attached in Appendix VIII, the sensitivity analysis can be used to address data-, model-, choice uncertainty as well as spatial-, temporal- and objective variability.[25] Due to the versatility possibilities to address different types of uncertainty, a sensitivity analysis is implemented in the present study.

2.3 Challenges for Comparative Life Cycle Assessments

The purpose of comparative LCAs is the analysis of comparative considerations of potential environmental life cycle effects of different product systems. The result of a comparative survey between two products with the same purpose is a comparative statement about the ecological advantage of one product or the equality of the products. In order to receive objective outcomes from comparative studies specific determinations according to the ISO standards 14040 and 14044 have to be considered. Especially the formulation of goal and scope definition has to be observed. Requirements for a comparative LCA are the same function, quantified by the same functional unit(s) of the assessed products. Furthermore the scope definition has to specify the efficiency of the analyzed product systems as well as system boundaries, data quality requirements and the allocation procedure. It has to be equivalent for the comparative product systems.[26] A weighting process is not allowed. Moreover, an evaluation of the

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22 Cf. HEIJUNGS, R.; HUIJBREGTS, M. A. J. (2004), p.1 et seq.
23 Cf. WEIDEMA, B. P.; WESNAES M. S. (1996), p. 168 et seq.
24 Cf. HEIJUNGS, R.; HUIJBREGTS, M. A. J. (2004), p.4 et seq.
25 Cf. BJOERKLUND, A. E. (2002), p. 70.
26 Cf. DEUTSCHES INSTITUT FÜR NORMUNG E. V. (eds.) (2009), p. 17.

LCIA results regarding sensitivity has to be implemented. Any differences regarding the comparability between the systems must be identified and reported. The main requirement of comparative studies reflects the unrestricted transparency.[27]

[27] Cf. DEUTSCHES INSTITUT FÜR NORMUNG E. V. (eds.) (2009), p. 44 et seq.

3 State of the Art

This chapter gives an overview of the relevant research literature for LCA of the wood industry especially for forestry products and products from SRC. Firstly, the method of the literature research is described. Secondly, an overview of previously evaluated wooden products from conventional forestry and SRC is given. The reviewed literature is further constrained in order to focus only on relevant literature for the comparison of both types of wood. Following this detailed examination of relevant literature the research questions are derived.

3.1 Method of the Literature Research

The following sections display the strategy pursued in order to detect relevant literature. Search strings were chosen if they described wood, wood products, forestry as well as SRCs in combination with search strings for LCA and cascading. Thereby, German and English terms were used to gather international as well as German-language literature. A list of the relevant search strings is attached in Appendix II. German and English databases were chosen to search for keywords described above. Relevant databases are associated to the branches of forestry, environment, technique, economics and agricultural. Additionally, aiming a comprehensive research, the search engine “Google Scholar” was used. Furthermore, the websites of German ministries and institutes for agriculture and forestry were observed to find literature about the cultivation of SRC and conventional forestry. Further information is listed in Appendix I.

Finally 74 articles could be found. Articles were relevant if, after analyzing title and abstract, it could be noticed that the central issue of the article is:

- LCA/ LCI about wood or wooden products (energetic/ material usage)
- LCA/ LCI about forestry or SRC
- Cascading / respectively cascading and LCA
- Planting and cultivation of SRC / forestry

A list of articles which directly examined the LCA of wood or wooden products of conventional forestry or SRC is attached in Appendix III and Appendix IV displaying the author issue and scope. This information is essential getting an overview of previous studies.

3.2 Literature Review

This chapter provides an overview on previous LCA studies based on the following scheme: First, current LCA studies of wooden products of SRC and conventional wood are described. Additionally, an overview of the assessed products is given. Finally, relevant literature is examined.

3.2.1 Wood from Conventional Forestry

In order to receive a broad understanding of LCA for wood, the first LCAs focusing on wood production itself need to be described. ZIMMER, B.; WEGENER, G. (1996) published one of the first articles about LCA of wood products. They analyzed the first two stages of a wood product: the wood production in forestry as well as the manufacturing of a wooden product.

The authors criticized that besides a technical production of wood, the important aspect of biological wood production in the forest was poorly or even not included in the existing literature of LCA for the wood industry.[28]

The technical production describes the stages of wood -cultivation, -harvesting and wood provision. The wood cultivation comprises operations for the development of the forest, e.g. crop establishment, road building and tree fostering. A further technical aspect is the thinning of small diameter wood for the sorting of weak trees. Through the harvesting and provision processes the product “wood” can be supplied for further utilization processes regarding an energetic or material usage.[29] However, the important aspect of biological wood production, which represents the crucial difference between renewable and non-renewable resources, was examined insufficiently.

Thus, ZIMMER, B.; WEGENER, G. (1996) particularly analyzed, the biological production of wood for one ton of round logs of spruce, pine, beech and oak. Due to the complexity of the biological production of wood and the ecosystem forest, the authors limit their analysis to the wood production itself. Figure 4 exemplarily shows the biological production of 1000 kg (bd) wood which conforms to the process of photosynthesis. Figure 5 illustrates the steps of the production of wood from conventional forestry.

$$6\ CO_2 + 12\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

$$\downarrow$$

$$8{,}4\ CO_2 + 12\ H_2O \rightarrow C_{8,4}H_{12}O_{5,4} + 8{,}7\ O_2 + 6\ H_2O$$

$$\downarrow$$

$$1854\ \text{kg}\ CO_2 + 1048\ \text{kg}\ H_2O \rightarrow \mathbf{1000\ kg\ Holz} + 1396\ \text{kg}\ O_2 + 542\ H_2O$$

Figure 4: Equation of the wood building process through photosysnthesis
(modified after: ROEDL, A. (2008), p. 13, according to: ZIMMER, B.; WEGENER, G. (1996), p. 217 et seq.)

[28] Cf. ZIMMER, B.; WEGENER, G. (1996), p. 217 et seq.
[29] Cf. BAUER, C. (2007), p. 16.

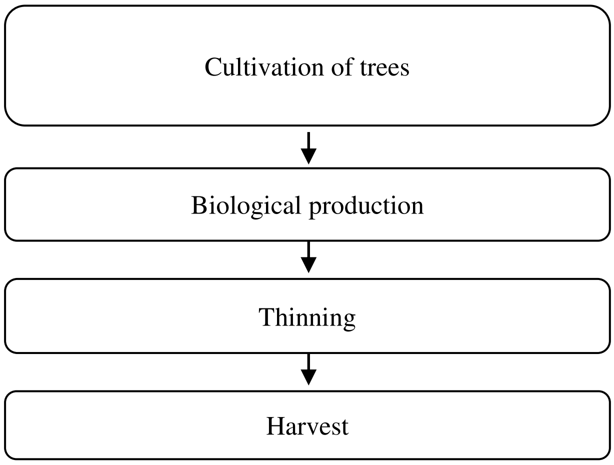

Figure 5: Production of wood from conventional forestry
(modified after: BAUER, C. (2007), p. 17)

The authors further describe the part of technical production as production processes of an active intervention of humans to affect wood production regarding quality and dimension. Thus, the intensity of the technical production has a crucial effect to the LCA of wood.[30] In consequence of the high variety of the different types of forests ZIMMER, B.; WEGENER, G. (1996) also used simplified assumptions for their LCA which were previously defined by SCHWEINLE, J. (1996):

- Same site conditions for all forest resources
- Independent from their age all stocks of one tree species have the same yield classes
- Trees of all ages are present
- The gradient has a maximum of 35%
- Logging trails are existing every 25 meters[31]

Moreover, RICHTER, K.; GUGERLI, H. (1996) point out that wood has an exceptional position due to the fact that wooden products are made from a raw material which is a component of an ecosystem itself. They also criticize, that with exception of the storage of CO_2, social services of forestry were not taken into account. Social services are e.g.: biodiversity, the forest as a place for recovery or the forest as a filter for air and water.[32]

Figure 6 shows the identified life cycle stages for wooden products from conventional forestry.[33] For reasons of illustration the life cycle stages are shown in a simplified scheme. However, by means of the identified stages it is possible to show the approaches of previous LCA studies of wood and wooden products. The first life cycle stage “Wood production” considers the processes of biological and technical production of wood. The “Wood Transformation Phase” comprises the processing of wood to wooden products for energetic or material usage, e.g., producing pellets for energetic use or producing saw wood for the industrial sector. This

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30 Cf. ZIMMER, B.; WEGENER, G. (1996), p. 217 et seq.
31 Cf. SCHWEINLE, J. (1996), p. 46 et seq.
32 Cf. RICHTER, K.; GUGERLI, H. (1996), p. 225 et seq.
33 Cf. FRUEHWALD, A.; SCHARAI-RAD, M.; HASCH, J. (1997), p. 10.

stage also includes the storage of wood for a certain time in order to influence wood quality with respect to the humidity of wood.[34] The humidity of wood is a key factor for the material and energetic usage. Beside the density, humidity influences heat value and efficiency of firing.[35] The “Utilization Stage” describes the energetic or material usage of wood, e.g. the combustion of pellets or the utilization of wooden floors. A “Recycling Stage” is only possible for material wooden products, e.g., the usage of pre-used industrial wood for the production of woodchips for particleboards, or the usage of pre-used particleboard for other wooden products and so on.[36] Due to the versatility of wood, recycling is most meaningful from an ecological and economical point of view. Within the issue of recycling of wood, the cascade utilization of renewable biomass has to be considered:

Based on a scarcity of fossil resources, an increasing demand for wooden biomass and a limited area for the cultivation of biomass, cascading is an important approach to increase the efficiency use of raw materials.[37] ARNOLD, K. et al (2009) mention three possibilities to use renewable resources in an ecological sensitive way: First, the usage of byproducts, second, the parallel usage of one product, e.g. the energetic and material usage of wood. Thirdly, a cascade utilization which means, that a product is firstly used for material purposes and finally for energetic ones. In other words, cascading is a successive usage of the same biomass, initially in the material sector for multiple products and finally in the energetic one. Advantages of cascading are an efficient utilization of land and resources as well as the avoidance of fossil energy, which leads to an advantage for climate protection.[38] Especially through a cascade utilization of wooden materials, carbon is locked up in the wood and stays there for a longer time span. Hence, CO_2 emissions can be postponed. However, for SIRKIN, T.; HOUTEN, M. (1994) cascading starts at a high resource quality, but with an increasing life time and several recycling steps there is a certain quality loss per application.[39] Beside that problem, studies confirm that there are less environmental burdens for the material usage of renewable resources but not for the energetic one. Moreover, postponing CO_2 through the application of wooden products is only sensible with a sustainable forestry. At least, cascading is just ecological useful if the amount of resources for the recycling process is not higher than for a new production of the product. However, FRAANJE, P. (1997) recommends a cascading of the renewable resource wood. The author argues that it increases the overall life time and therefore the efficiency of resource usage significantly[40] ARNOLD, K. et al. (2009) describe general requirements on a sustainable cascading:

- A sustainable production of biomass, which means the protection of environment and humans.
- An efficient production and processing, which means the utilization of byproducts and a final energetic usage.
- A repeated material utilization within the limitations of recycling.

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34 Cf. BAYRISCHE LANDESANSTALT FÜR FORST UND LANDWIRTSCHAFT (eds.) (2011), p. 19.
35 Cf. BAUER, C. (2007), p. 13.
36 Cf. RIVELA, B. et al. (2005), p. 106 et seq.
37 Cf. ARNOLD, K. et al. (2009) p. 7 et seq.
38 Cf. ARNOLD, K. et al. (2009) p. 18 et seq.
39 Cf. SIRKIN, T.; HOUTEN, M. T. (1994), p. 214 et seq.
40 Cf. FRAANJE, P. (1997), p. 28.

- An adaptation of product characteristics towards a sustainable product design and an easier reusability.
- Flexible production conditions to enable a cascaded utilization.
- A decreasing demand of products through a changing attitude of costumers, to increase the efficient use of resources.[41]

The last life cycle stage of wood is “Disposal”. It contains the combustion or putrefaction of wood e.g. for energetic purposes. A removal through combustion includes the disposal of ash.[42]

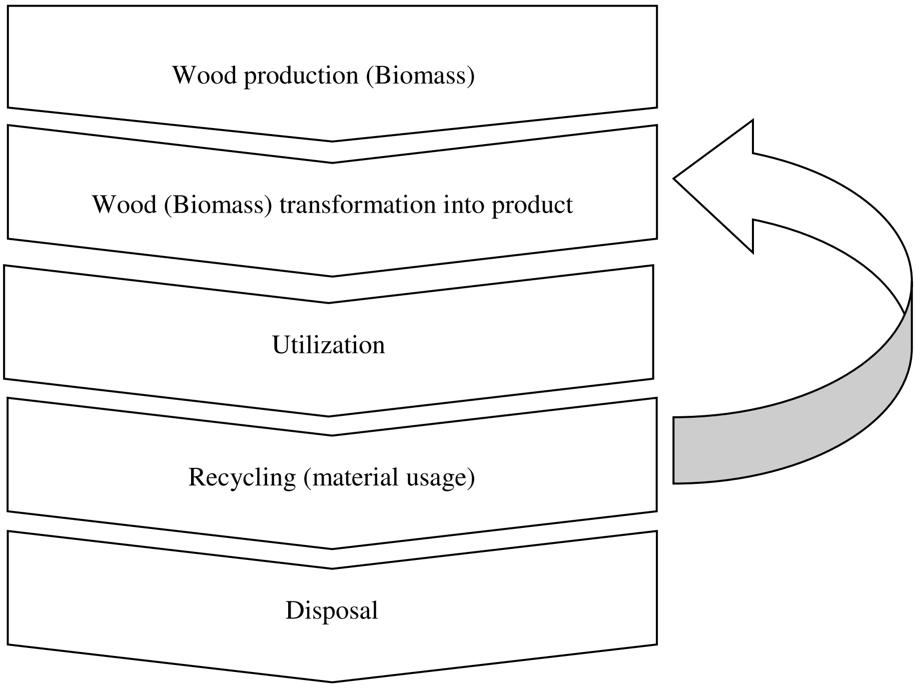

Figure 6: Life cycle for a conventional wooden product
(Own illustration.)

Appendix III provides an overview about the articles of LCAs for conventional wood. The table in Appendix III follows the same structure as Figure 6. To optimize the overview, the table is divided in wooden products for material- and energetic use. The considered life cycle stages of the respective study are marked with an “X”. 13 articles could be identified which examine the LCA of wooden products for material usage. 12 articles could be identified which examine the LCA of wooden products for energetic usage. First LCAs for products from conventional wood are from 1996, whereby until 2002 only LCAs of wood for material usage were implemented. From 2002 until now an increasing tendency for LCAs of wood for energetic usage is discernible. By the end of the nineties scientists of the research areas forestry and forest management, respectively, were dissatisfied with LCA studies on wood or wooden products.[43] Hence, like mentioned above, first LCAs concentrated on the examination of the biological and technical production of wood. Later LCAs of wooden products were added, first concern-

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41 Cf. ARNOLD, K. et al. (2009) p. 27 et seq.
42 Cf. JUNGBLUTH, N.; FRISCHKNECHT, R.; FAIST, M. (2002), p. 24 et seq.
43 Cf. ZIMMER, B.; WEGENER, G. (1996), p. 217.

ing products like industrial wood, particleboards, windows, floors and secondly for products for energetic usage like woodchips and pellets. It is conspicuous that LCAs of wood products for material usage often follow a gradle to gate approach. Thus, the life cycle stages "Utilization", "Recycling" and "Disposal" are neglected. Four LCA studies examined the whole life cycle of a wooden product for a material usage. LCAs of wooden products for energetic usage usually examine til the production or utilization stage of the life cycle (e.g., the production of woodchips plus the combustion of these chips in a biomass power plant). However, two articles consider the whole life cycle of an energetic product, including "Disposal".

Figure 7 illustrates a comprehensive overview about previous LCA studies of products from conventional wood for energetic and material usage. As it can be seen, LCA studies exist for a wide range of material- and energetic products.

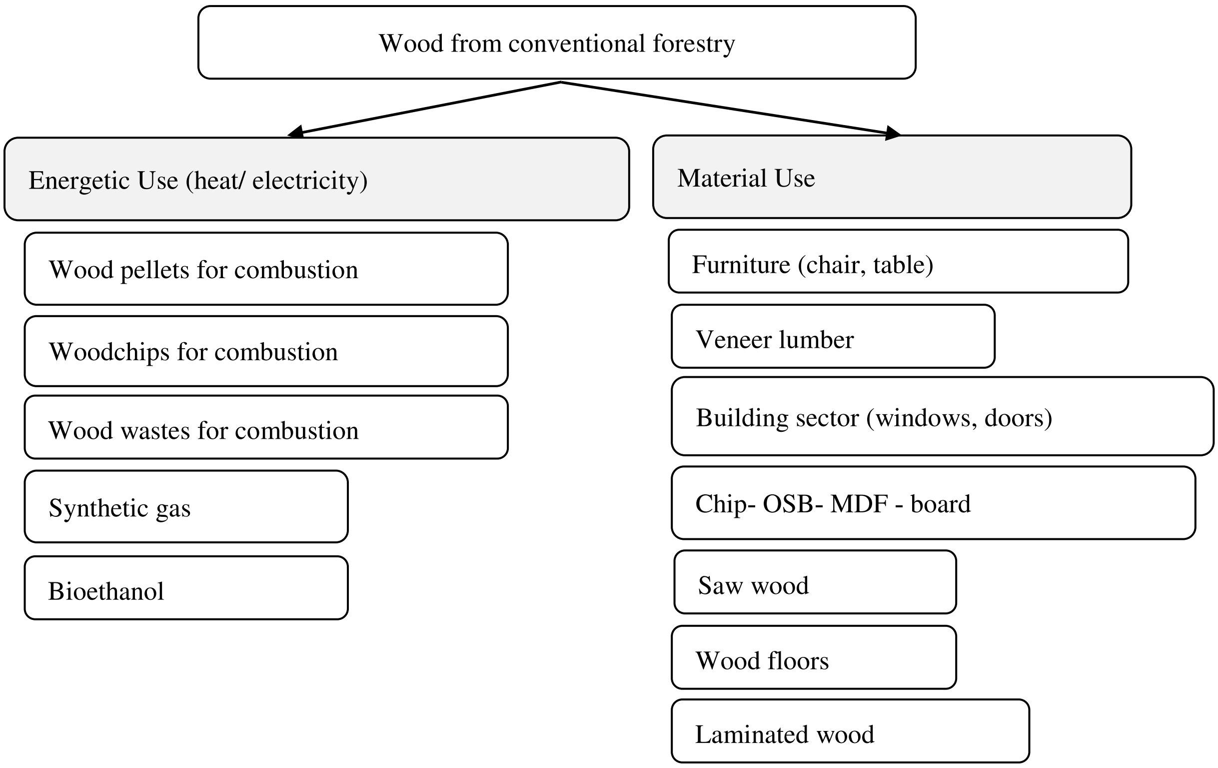

Figure 7: Previous LCA studies for products from conventional forestry (Own illustration.)

3.2.2 Wood from SRC

An SRC is a planting of fast growing coppice on agricultural areas, which is managed more intensively than usual forestry practices for a quicker production of wooden biomass.[44] BURGER, F. (2010) and ROEDL, A. (2008) evaluated different cultivation and harvesting methods for SRC. The authors adopted the idea of ZIMMER, B.; WEGENER, G. (1996) and assessed the biological and technical production of wood from SRC.[45] Because both times the raw material wood is evaluated, there are almost the same life cycle phases for SRC: the biological production of wood from SRC conforms to the biological wood production of conven-

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[44] Cf. ROEHRICHT, C.; RUSCHER, K. (2009), p. 4.
[45] Cf. BURGER, F. (2010), p.85 et seq.; Cf. ROEDL, A. (2008), p. 9 et seq

tional wood. However, the technical production comprises planting, fostering, (fertilization – just optional), harvesting and clearance. At the beginning of the planting process the soil has to be prepared mechanically and chemically with an herbicide to destroy existing weed. Afterwards, scions, which were grown in a tree nursery, are cultivated by planting machines. During the growing period trees have to be fostered through a mechanical removal of weed and understory vegetation.

Fertilization is not necessarily required. The study of ROEDL, A. (2008) analyzed the production of wood from SRC once with fertilization and once without. However, no significant yield increases could be noticed through fertilization.[46] Furthermore, studies of BOELKE, B. (2006) and RÖHRICHT, C.; RUSCHER, K. (2004) did not report yield increases through fertilization as well.[47] The harvest of SRC trees can be implemented up to four times. The harvests ensue after a rotation period of four years, leading to a total quantity of 16 years.[48] Finally, the clearing process is implemented. Clearing describes the removal of all wooden components like roots and tree stumps after using the agricultural area for SRC.[49] Figure 8 illustrates the production of wood from SRC.

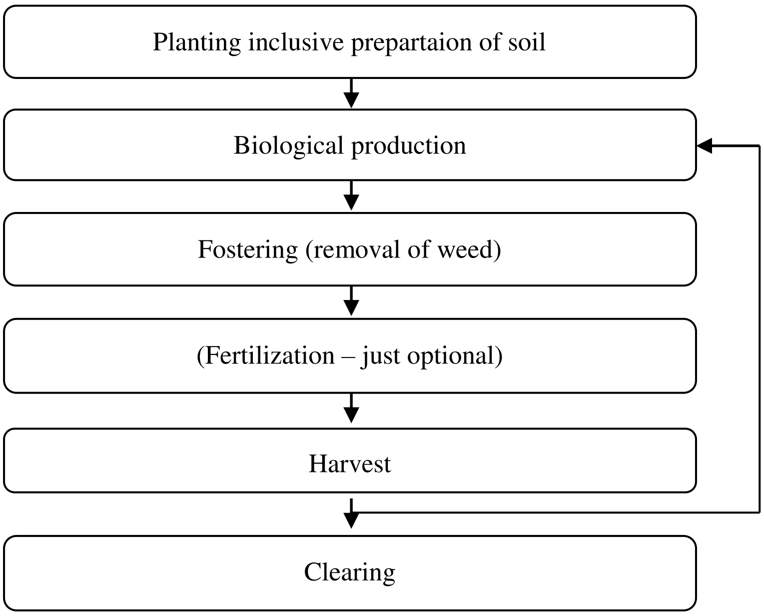

Figure 8: Production of wood from SRC
(Source: modified after ROEDL, A. (2008) p. 7.)

Figure 9 shows the identified life cycle stages of a wooden product from SRC. In contrast to life cycle phases for wood from conventional forestry, no recycling process could be recognized; due to LCA studies for material usage of wood from SRC could not be identified. However, the process “Clearing” has to be included.[50] Like for conventional wood there is a production-, transformation-, utilization- and disposal- stage.

[46] Cf. ROEDL, A. (2008), p. 15 et seq.
[47] Cf. ROEDL, A. (2008), p. 15 et seq, according to: BOELKE, B. (2006), p. 16; RUSCHER, K. (2004), p. 2.
[48] Cf. ROEDL, A. (2008), p. 9 et seq.
[49] Cf. BOELKE, B. (2006), p. 23 et seq.
[50] Cf. ROEDL, A. (2010), p. 569.

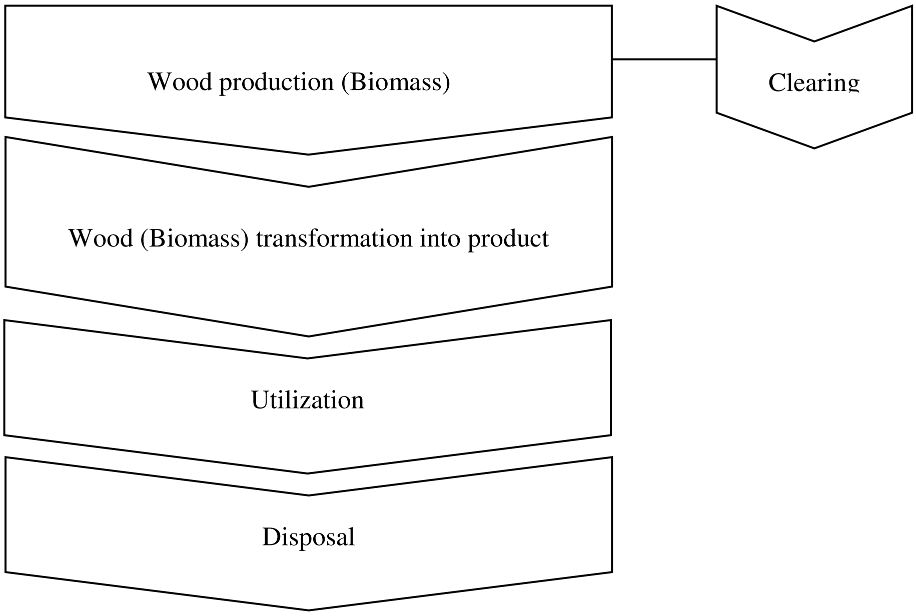

Figure 9: Life cycle for a wooden product from SRC
(Own illustration.)

Appendix IV shows the articles which addressed LCAs of wood from SRC. The table of Appendix IV follows the same structure as Figure 9. Ten articles were found which evaluate LCA for wood from SRC. The first article was published in 1999. However, most articles were published between 2008 and 2012. Seven of ten articles examine the LCA from the "Wood Production Stage" till the "Utilization Stage". The process "Clearing" is considered nine of ten times whereby the last phase "Disposal" is included in three articles. It is notable, that all articles examine wood from SRC for an energetic utilization, e.g., the production and utilization of woodchips for electricity or heat production.

Figure 10 illustrates previous LCA studies on products from SRC. Obviously there are not as many LCA studies for products from SRC as for products from conventional wood.

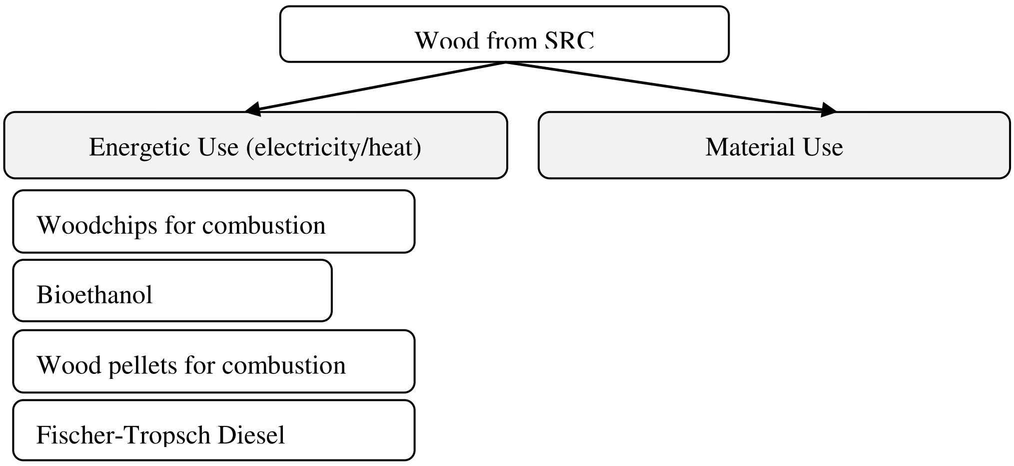

Figure 10: Previous LCAs for products from SRC
(Own illustration.)

3.2.3 Conclusions of Literature Review

The aim of the present study is to identify the ecological impacts of wood from SRC in comparison with wood from conventional forestry. A critical evaluation of previous literature showed that comparisons regarding SRC exist for an:

- LCA which examines the electricity production from poplar energy crops compared with fossil fuels.[51]
- LCA study analyzing the ethanol production of different fast growing wood crops.[52]
- Comparisons for conventional wood exist for:
- LCA which compares the avoided ghg emissions when using different kinds of wood energy.[53]
- LCA which compares the electricity production from used wood.[54]
- LCA which compares different wooden building products.[55]
- LCA which compares the energetic and material use of waste wood.[56]

Furthermore, the literature review reveals studies, which assess the production and combustion of wood from conventional forestry and wood from SRC, respectively:

- The production of woodchips[57]
- the production of pellets[58] and
- the combustion of these products[59]

were analyzed for both types of wood. Unfortunately, a comparison between conventional wood and wood from SRC based on a comparison of the reviewed studies wouldn't be recommendable. Due to different approaches and criteria, such as different system boundaries, different input/output factors and different allocation procedures, the comparison would be inaccurate.[60] Furthermore, current LCA studies of wood from SRC are not assessing material use.

Thus, a direct comparison between both types of wood has to be implemented in order to meet the goal of the present study. Additionally, in order to close the scientific gap regarding a material usage of wood from SRC and to get decision guidance from an ecological point of view concerning the increasing conflict between material and energetic usage of wood, the comparative LCA should include the aspects of an energetic and material use. This idea is also supported by JUNGMEIER, G. et al. (2002) which point out that LCAs of wood should concentrate on the twofold nature of it.[61] That approach is pursued in the present study to give a

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51 Cf. RAFASCHIERI, A.; RAPACCINI, M.; MANFRIDA, G. (1999), p. 1477 et seq.
52 Cf. GONZÁLEZ-GARCÍA, S. et al. (2012), p. 456 et seq.
53 Cf. PETERSEN RAYMER, A. K. (2006), p. 605.
54 Cf. JUNGBLUTH, N.; FRISCHKNECHT, R.; FAIST, M. (2002), p. 1.
55 Cf. RICHTER, K.; GUGERLI H. (1996), p. 225.
56 Cf. RIVELA, B. et al. (2005), p. 106.
57 Cf. BURGER, F. (2010), p. 1.; Cf. ZIMMER, B. (2010), p. 22
58 Cf. PA, A.; BI, X. T.; SOKHANSANJ (2011), p. 167.; Cf. FANTOZZI, F.; BURATTI, C. (2010), p. 1796.
59 Cf. ELTROP, L. et al. (2006), p. 10 et seq.; Cf. MURACH, D.; KNUR, L.; SCHULTZE, M. (2002), p.3.
60 Cf. FRUEHWALD, A.; SOLBERG, B. (1995), p. 11.
61 Cf. JUNGMEIER, G. et al. (2002), p. 291.

comprehensive overview on the ecological aspects of wood from SRC in comparison with conventional wood. Hence, wooden products have to be chosen which can be manufactured from both types of wood for both purposes.

Woodchips represent a wooden product that considers all the requirements described before. They can be made from SRC and conventional wood. Thereby, a material usage is possible for all products with lower requirements of the wooden quality. Energetic usage is possible through the combustion of woodchips for energetic purposes.[62] One important product based on woodchips are particleboards.[63] Additionally, studies from ROFFAEL, E.; DIX, B. (1988), and WILCZYNSKI, A. (2011) approved the utilization of wood from SRC for the production of the core layer (interior layer) of a particleboard.[64]

Thus, a particleboard made of woodchips plus the production of bioenergy through woodchips combustion is chosen to compare both types of wood regarding energetic and material usage from an ecological point of view. Implementing the chosen approach, the following chapter concentrates on the literature for the issues mentioned above.

3.2.4 State of the Art regarding Manufacturing Particleboards and Bioenergy from SRC and conventional Wood

This chapter firstly observes recent literature of conventional wood for the production of particleboards and regarding an energetic usage. Afterwards the literature for SRC is examined concerning energetic usage. As described in chapter 2.2.2 LCA studies about a material usage of wood from SRC could not be identified.

Conventional wood

Particleboard

WEGENER, G.; FRÜHWALD, A.; SCHARAI-RAD, M. (1997) implemented an LCI study for the production of $1 m^3$ particleboard. The authors point out that the production of particleboards has special characteristics which have a great impact on LCI and LCA, respectively: On the one hand the different wood moisture, because particleboards can be made of different types of wood, on the other hand there is the intern utilization of waste wood, which is accruing beside the production phase. As a result this LCA study shows that during the particleboard production emissions in the air have a higher quantity than emissions for water and soil.[65] Another LCA study was implemented by RIVELA, B. et al. (2005). The authors analyze the whole life cycle (gradle to grave) of $1\ m^3$ particleboard in a Spanish factory by on-site-measurements with different kinds of wood. The process chain for particleboard manufacturing is subdivided in three main subsystems: wood preparation, board shaping and board finishing with the subsystems of the transport, chemical and energy consumption.[66] The impact assessment, implemented with the Ecoindicator 99 methodology shows, that the board finishing subsystems has the greatest impact on the impact categories as it is the subsystem

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62 Cf. BAUER, C. (2007), p. 54 et seq.
63 Cf. ROFFAEL, E.; DIX, B. (1988), p. 245.
64 Cf. WILCZYNSKI, A. et al. (2011), p. 194.; Cf. ROFFAEL, E.; DIX, B. (1988), p. 245 et seq.
65 Cf. WEGENER, G.; FRÜHWALD, A.; SCHARAI-RAD, M. (1997), p. 16 et seq.
66 Cf. RIVELA, B. et al. (2005), p. 106 et seq.

that mostly dependents on the use of electricity. It accounts for 93 percent of the damage to human health. The contribution of gas coming from driers had a significant impact to the Ozone layer category with a value of 91 percent. The board shaping subsystem has a great contribution to the damage to ecosystem quality. Additionally, the authors underline the importance of an effective and efficient use of wood including products with longer service life and final incineration with an energy recovery. They encourage the reuse and recycling of wood with the evidence, that the more wood is reprocessed, the more restricted its potential applications are, including the investment of non-renewable energy and material for reprocessing.[67] FRÜHWALD, A.; RAD-SCHARAI, M.; HASCH, J, (2000) analyzed particleboards for dry (standard particleboards) and wet areas. Particleboards have an advantageous CO_2 balance if wood is coming from sustainable forestry. Energy demand is a crucial factor for the impact categories acidification, ozone formation and eutrophication. Especially the combustion of wood and oil is unfavorable. Thus, the authors recommend "end of pipe" technologies like particle filters to reduce nitric oxide emissions. The consumption of glue and binder considerably contributed to acidification and ozone formation. Whereby there are very low environmental burdens through the consumption of wood (mass portion of 90 percent).[68]

Energetic Usage

ZIMMER, B. (2010) considered the energy production through woodchips from an environmental point of view. Four forestry scenarios, which differ with respect to professionalism, harvesting and logistics, were evaluated with the result that woodchips have high energy efficiency, with the drawback that the use of fossil fuels in the production phase of wood is still dominating. Further results show that transports worsen the energy balance, thus the author recommends a railway siding for biomass power plants bigger than 20 MW. There is great ecological potential for the quality of woodchips and their storage. A high quantity of moisture content and an incorrect storage leads to a decreasing level of efficiency in biomass power plants and therefore to increasing environmental burdens. The efficiency of power plant strongly influences on LCA of woodchips as well. Moreover, the highest level of energy efficiency through the cascading principle is recommended. Another important aspect is a substitution effect which accrues through the combustion from wood as energy provider. Energy from wood lowers the demand of fossil fuels. This CO_2 saving potential of wood should be considered in LCAs.[69] ELTROP, L. et al. (2006) assessed different energy and heat production systems based on wood fuels in comparison with fossil fuels. As a result the authors show that a high degree of mechanization is cost efficient due to lower working hours but is also most environmental unfriendly due to high expenditures of fossil fuels. The authors recommend an optimal adaptation to local circumstances for a minimum of environmental burdens. Further outcomes of the analysis show that CO_2 emissions are much lower if wooden products are used for energy production. However, particle emissions are higher for wooden products which should be constrained through filters or purification cleaners. Moreover it could be

[67] Cf. RIVELA, B. et al. (2005), p. 112 et seq.
[68] Cf. FRUEHWALD, A.; RAD-SCHARAI, M.; HASCH, J, (2000), p. 114 et seq.
[69] Cf. ZIMMER, B. (2010), p. 22 et seq.

shown, that most environmental damages are arising during the combustion process of wood. As a final result, the authors advocate for an expansion of using wood as an energy source.[70]

Wood from SRC

Energetic Usage

As shown in chapter 3.2.2, one of the first LCA studies about SRC appeared by ROEDL, A. (2008). The study analyzes the environmental impact of willow-, locust- and poplar trees concerning cultivation with and without fertilization. Thereby, wood production and harvesting was analyzed. Utilization of wood as well as the environmental burdens of the production of machines, infrastructure and buildings are not regarded in this study. The author points out, that the production of renewable resources includes the environment (air, soil, etc.) as a part of the production system. Therefore, environmental aspects should be considered as production factors. Due to insufficient scientific methods this leads to problems for specific environmental issues such as the storage of carbon in the soil, which are not considered in these LCA. A quantity of carbon in the soil occurs during the growing period of the trees. The detailed reflection of this issue would be going too far in the present study. Furthermore it is not considered in LCA of ROEDL, A. (2008) and BURGER, (2010). Detailed information are presented in ROEDL, A. (2008).[71]

Outcomes of this LCA study show that harvesting accounts for the largest part of the environmental burdens through the utilization of fossil fuels for machines. Furthermore it is shown that environmental burdens increase with fertilization. However, woodchips from SRC have a negative global warming potential and low environmental burden regarding eutrophication and acidification.[72] In a further study ROEDL, A. (2010) evaluated two utilization paths of poplar chips: the energy generation in a cogeneration plant and the production of Fischer-Tropsch-Diesel. The study includes the production and harvest of biomass as well as transports and the disposal of ash. The CO_2 uptakes in the soil as well as infrastructure were not taken into account. Results of the study show that using fertilizer cause great differences on the impact category results. Moreover, the weight of the transported biomass, depending on the water content of wood, is crucial. The higher the moisture of the transported wood, the higher the weight and the higher the energy consumption and environmental impacts are, respectively.[73] Another comprehensive LCA for SRC was implemented by BURGER, F. (2010). The author analyzed the wood production, harvesting and energetic utilization of balsam poplar under consideration of seven harvesting methods. Unlike ROEDL, A (2008), the preceding chains of the harvesting machines were assessed too. Human power was not considered. Furthermore, this study renounces fertilization as well as the assessment of the alteration of carbon balances in the soil. Additionally he points out that cultivation of SRCs is an extensive land use. Further results of the LCA show that harvesting and clearance have the highest energy input. The produced woodchips were used for combustion in a 300 kW woodchip heating system and a 1,4 MW cogeneration plant. The analysis of the combustion indicated that

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[70] Cf. ELTROP, L. et al. (2006), p. 49 et seq.
[71] Cf. ROEDL, A. (2008), p. 14 et seq.
[72] Cf. ROEDL, A. (2008), p. 50 et seq.
[73] Cf. ROEDL, A. (2010), p. 573 et seq.

caused by electric engines in the woodchip heating system, there is a high electricity consumption.[74] HELLER, M.; KEOLEIAN, G.; VOLK, T. (2002) also deal with an LCA study concerning energy generation from SRC. The authors analyze the environmental burdens from biological production up to the combustion of willow woodchips. It could be shown that willow biomass crops are sustainable from an energy balance perspective and also contribute to additional environmental benefits. However, like in previous studies reported, fertilization and harvesting accounts for the majority of primary energy consumed[75] Another LCA from GOGLIO, P.; OWENDE, P. (2009) evaluates two small scale electricity generation pathways based on willow biomass. The study included the production and utilization of willow chips. The authors found out, that the chip drying technique has significant impact on the net energy production: Exhaust recycling enhances the energy efficiency and therefore the environmental compatibility. Again, it could be shown that fertilizing is a major determinant in the process life cycle. Furthermore, the authors show that the chip transportation distance is a major cause of variations of the net energy production and total CO_2 emissions. A transportation distance smaller than 38 km significantly reduces the energy output- input ratio.[76] Additionally RAFASCHIERI, A.; RAPACCINI, M; MANFRIDA, G. (1999) suppose that the use of biodiesel could reduce CO_2 emissions and life cycle environmental impacts.[77]

3.2.5 Deriving Research Questions

Due to different LCA approaches only general assertions about the particleboard production and energetic usage of the wood types seem helpful for a comparative LCA. Summarizing the literature for the production of the particleboard from conventional wood shows that particleboards have an advantageous CO_2 balance if wood comes from sustainable forestry.[78] The environmental burdens of the production depend on the wood moisture and the implementation of an intern utilization of waste wood; arising during the production process.[79] End of pipe technologies like particle filters are recommended.[80] Dividing the production into subsystems, one study shows that the contribution of gas for drying processes has a significant impact to the ozone layer category; the board shaping subsystem has a significant impact to the damage of the ecosystem quality.[81]

Summarizing the energetic usage of woodchips from conventional forestry shows that fossil fuels are still dominating in the wood production and harvesting.[82] A high degree of mechanization is also most environmental unfriendly due high expenditures of fossil fuels. Thus an optimal adaptation to local circumstances is recommended. However, most environmental damages are arising during the combustion process of wood.[83] Furthermore a high quantity of moisture content, an incorrect storage and a low efficiency of the power plant can lead to

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74 Cf. BURGER, F. (2010), p. 83 et seq.
75 Cf. HELLER, M.; KEOLEIAN, G.; VOLK, T. (2003), p. 160 et seq.
76 Cf. GOGLIO, P.; OWENDE, P. (2009), p. 390 et seq.
77 Cf. RAFASCHIERI, A.; RAPACCINI, M; MANFRIDA, G. (1999), p. 1491.
78 Cf. FRUEHWALD, A.; RAD-SCHARAI, M.; HASCH, J, (2000), p. 114 et seq.
79 Cf. FRUEHWALD, A.; SCHARAI-RAD, M.; HASCH, J. (1997), p. 16 et seq.
80 Cf. FRUEHWALD, A.; RAD-SCHARAI, M.; HASCH, J, (2000), p. 114 et seq.
81 Cf. RIVELA, B. et al. (2005), p. 1 et seq.
82 Cf. ZIMMER, B. (2010), p. 22 et seq.
83 Cf. ELTROP, L. et al. (2006), p. 1 et seq.

higher environmental burdens. Therefore they have a great influence on the LCA of the energetic use of woodchips.[84] Like for the production of particleboards, for the combustion of wood, particle emissions should be filtered.[85] However, energy from wood saves using fossil fuels. Thus, a CO_2 saving potential of wood can be considered in LCAs.[86]

Main facts for the production and utilization of wood from SRC are that besides the harvesting, fertilization has a major impact on environmental burdens. Both processes account for the majority of primary energy consumed.[87] It has to be noticed, that fertilization is not always been recommended. Studies proved that without fertilization the growth of the trees is not influenced. Hence, fertilization can be implemented according to the study requirements.[88] Results without fertilization indicate that harvesting and clearance have the highest energy input. Like for conventional wood, drying and storage of woodchips influences results of the LCA.[89] Furthermore, the energy input of transports of woodchips can be significantly reduced if transport distances are smaller than 38 km, if biodiesel is used and a low wood moisture is present.[90] For both types of wood social aspects and the storage of carbon in the soil weren't assessed.

Anyway, to fulfill the study aim, the production of a particleboard and bioenergy was chosen. Previous studies are unhelpful to compare the two types of wood, but can provide references and critical aspects which should be minded by implementing a comparative study. Furthermore, material usage of wood from SRC was not evaluated so far. Thus, following research questions have to be evaluated:

Research Question 1:

Which type of wood is more reasonable for energetic usage; regarding an environmental point of view?

Research Question 2:

Which type of wood is more reasonable for material usage; regarding an environmental point of view?

Research Question 3:

Is there an "ecological winner" in general?

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84 Cf. ZIMMER, B. (2010), p. 22 et seq.
85 Cf. JUNGBLUTH, N.; FRISCHKNECHT, R.; FAIST, M. (2002), p. 35 et seq.
86 Cf. ZIMMER, B. (2010), p. 22 et seq.
87 Cf. ROEDL, A. (2008), p. 50 et seq.
88 Cf. ROEDL, A. (2008), p. 15 et seq.
89 Cf. GOGLIO, P.; OWENDE, P. (2009), p. 390 et seq.
90 Cf. GOGLIO, P.; OWENDE, P. (2009), p. 391 et seq.

4 LCA Implementation

The LCA application follows the methodology as described in chapter 2.1. Impact assessment and data interpretation are summarized. Moreover a sensitivity analyses is implemented.

The Gabi 5 - software which was designed by PE International was the LCA-software used in the present study.[91] Several characteristics and calculations regarding wood and wood utilization are attached in Appendix V and XI.

4.1 Goal and Scope Definition

4.1.1 Goal of the study

Goal of the study is the assessment of the environmental impacts of the energetic and the material use of wood, respectively, from SRC compared to wood from conventional forestry in order to answer the research questions quoted in chapter 3.2.5. This issue is analyzed in two steps: The first part assesses the environmental burdens of energy production of the two wood types. The second part of the study evaluates particleboard production. Afterwards, a comparison of the different wood types will show the favorable alternative from an ecological point of view. With respect to the first part it has to be noticed, that due to a similar combustion of both woodchips types which is shown below, the comparison is focused on the production of woodchips for energy purposes. Nevertheless, combustion is shown with the example of the combustion of conventional wood to illustrate and discuss a whole life cycle of a wooden product used for energetic utilization. According to the ISO standard, this procedure is possible if it does not significantly change the overall conclusions of the study. Due to an almost equal combustion process, the procedure used in the present study does not change the conclusions and is therefore applicable. [92]

Figure 11 pictures the scenarios in order to present a clear overview. The most important environmental burdens related to the alternatives shall be identified and qualified to discuss the material and energetic use of conventional wood and wood from SRC. Furthermore, part 2 provides additional information concerning the question if a material usage of wood from SRC is ecological reasonable.

This LCA can be seen as a source of information for administrative bodies, institutes, suppliers and customers. It is further a decision support concerning material or energetic use of wood, respectively, from different sources. The outcomes of the analysis can be used to receive more information about SRC as a possible environmentally friendly alternative to conventional forestry.

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[91] PE INTERNATIONAL (eds.) (2012), w.p.

[92] Cf. DEUTSCHES INSTITUT FÜR NORMUNG E.V. (Eds.) (2006), p. 18 et seq.

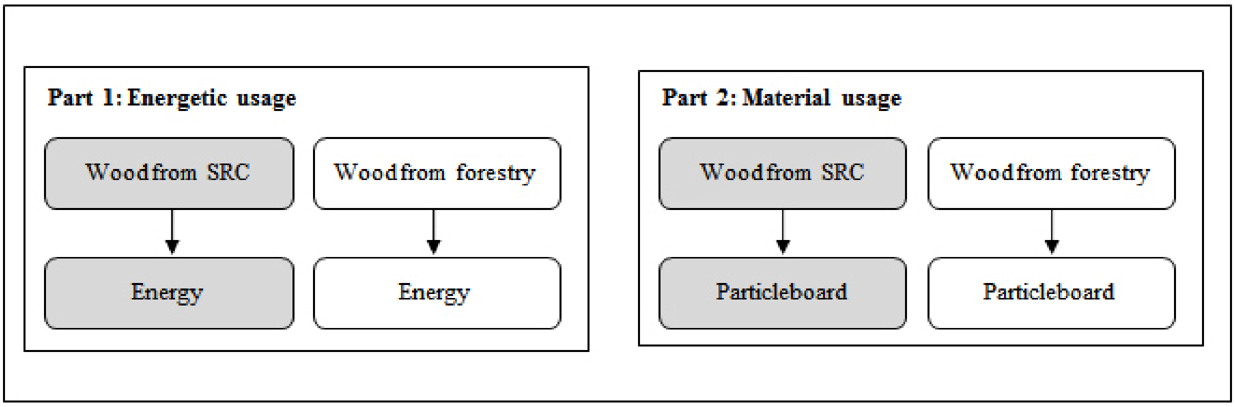

Figure 11: Parts of the study

(Own illustration.)

4.1.2 Functional Units

According to ROEDL, A. (2010) and as described before, it is useful to divide the study into two parts.[93] The first part assesses the energy production with woodchips from willow (wood from SRC) and woodchips from wood residues (conventional wood). A heat production in a 1000 kW automatic firing system with an efficiency between 83% - 94% is analyzed to produce **1 MJ of thermal energy**.[94] The combustion of woodchips is based on the low heating value of wood. Barked woodchips with humidity of 50 % are assumed. Moreover, the characteristic values of wood have to be considered. As shown in Appendix V, the characteristic values of willow and spruce regarding gross density, elasticity and solidity are slightly different. However, both woods are softwoods with approximately the same low heating value. Thus, the flammability of both woods is quite related: they both have a relative minor energy density and burn quickly. It is further assumed that both type of woodchips are provided of the same quality and size. The produced thermal energy can be used for district heating and industrial processes.[95]

The second part analyzes the production of **1 m^3** of a **three layer particleboard** with a core layer made of woodchips.

A factory representative of the state of the art is selected with a production capacity of 680 m^3 finished particleboard per day. The core layer is the interior layer made from coarse material such as woodchips. For conventional wood, woodchips from conifer industrial- and round wood (spruce); for wood from SRC, woodchips from willow are taken into account.

For the outside layers, which have to be fine particles on both surfaces for smoothness, industrial particles from sawdust are assessed for both types of wood.[96]

For both woods, pressing conditions with a temperature of 140-220°C and a maximum pressure between 2 - 3 MPa are assumed. Typical sizes of the particleboard are 4,880 mm×2,440 mm or 2,440 mm×1,220 mm with a ranging thickness from 8 mm to 45 mm.[97]

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[93] Cf. ROEDL, A. (2010), p. 568.
[94] Cf. BAUER, C. (2007), p. 29.
[95] Cf. BAUER, C. (2007), p. 25 et seq.
[96] Cf. RIVELA, B. et al. (2005), p. 108.
[97] Cf. RIVELA, B. et al. (2005), p. 107 et seq.

The shelling ratio (outside layers:interior layer) is about 40:60%.[98] Again, the characteristic values of willow and spruce have to be considered. As shown in Appendix V, they are slightly different.

However, the study of WILCZYNSKI, A. et al. (2011) shows that the mechanical properties elasticity, rupture, internal bond and thickness swelling of particleboards with the core layer made from willow and conifer wood respectively, are approximately the same. Particles made from willow are definitely technical suitable to substitute the industrial wood particles for manufacturing the core layer of a three-layer particleboard. Boards can be used for general purposes under dry conditions. They meet the requirements of the EN 312 standard for the particleboard of type P1.[99]

4.1.3 Product System

Part 1: Energy Production

Production of woodchips from conventional forestry

One requirement for the production of woodchips is the production of wood which was described in chapter 3.2 of the present study. However, processes of technical and biological production of wood shall be depicted summarized: The functional basis of the biological production of wood is photosynthesis. With the help of sun power, trees are producing wood substance by withdrawing oxygen, carbon and hydrogen from the atmosphere and soil.[100]

Technical production consists of crop establishment, tree fostering, thinning and harvesting. Additionally liming has to be considered. During the crop establishment young trees are planted after the area for wood production is cultivated through the building of forest roads and the harvesting of forest residues. Caring and protection measurements like browsing protection and the pruning of trees have to be implemented.[101]

At an appropriate tree size, a thinning process reduces the forest from small-perimeter trees. After a time of 50-70 years trees can be harvested for industrial wood. After the thinning or harvesting process, skidders depose logs next to a road near the forest.[102] For freshly harvested wood, a humidity of 120 percent is assumed. It has to be noticed; that for the production of woodchips for combustion mainly waste wood from thinning processes or wood residues from round wood are used. The concentrated wood residues get chopped by mobile, large scale wood chippers to produce woodchips. If woodchips are produced near the forest, they directly can be loaded into a returnable truck-container.[103] This container is used for the transport of woodchips by lorry to the firing system. Figure 12 illustrates the production of woodchips from conventional forestry.

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98 Cf. WILCZYNSKI, A. et al. (2011), p. 194 et seq.
99 Cf. WILCZYNSKI, A. et al. (2011), p. 194 et seq.
100 Cf. EBERHARDINGER, A. et al. (2009), p. 108 et seq.
101 Cf. RIEZINGER, A. (2008), p. 23.
102 Cf. ZIMMER, B., WEGENER, G. (1996), p. 218 et seq.
103 Cf. WITTKOPF, S.; HÖMER, U.; FELLER, S. (2003), p. 35 et seq.

Production of woodchips from SRC

The production of wood from SRC was particularized in chapter 3.2. However, like for conventional wood, a short summary shall be given: Again, there is a technical- and biological production of wood. The biological production is in accordance with the biological production of conventional wood.

The technical production comprises the processes: planting, fostering, harvesting and clearance. Fertilization is not implemented. For the planting process the soil gets prepared mechanically and chemically. The planting as well as the fostering is implemented mechanically. The harvests ensue after a rotation period of four years, leading to a total quantity of 16 years. The harvest is implemented by a mobile chopper, which is cutting the above grounded shoots. These shoots get transported to the cutterhead of the chopper where they get shredded into woodchips. Woodchips are gathered by a parallel driven lorry.[104] For freshly harvested woodchips a humidity of 120 percent is assumed. A flow chart shows the production of wood from SRC in Figure 13. Illustrations for wood from SRC are characterized with a broken line and grey fields.

Combustion of woodchips from conventional forestry and SRC

The combustion for both types of wood is equal and therefore summarized below:

Woodchips get transported by lorry to the firing system. At the firing system woodchips get stored in a silo.[105] Once the air dried woodchips receive a humidity of 50 percent, they finally get burned in an automatic firing system. Thereby, woodchips are transported to the furnace by an electric operated screw-conveyor. In the furnace, woodchips are transformed into CO_2 and water (as complete as possible) at a temperature of 800°C – 1300°C. - The combustion process consists of the phases: drying, decomposing of wood into carbons and fluids, converting of the carbons into fluids, oxidation of fluids.[106]

As a first step, wood gets dried and water steam is releasing. At a temperature of 150°C – 600°C and a supply of primary air through fans, wood gets converted into carbons, hydrogen and hydrocarbons. About 85% of the dry wood pulp gets converted into fluids; about 15% remains as charcoal. Subsequently, the combustion of the fluids follows with a temperature increase to 1000°C. Afterwards the charcoal scorches. Thermal heat arises for heating purposes.[107]

Finally, ashes get deposed. There are two kinds of ashes arising during the combustion of wood: slag (bottom ash) and filter ash. For larger firing systems (1000 kW) the ash usually gets deposed on a landfill.[108] Figure 14 shows the combustion of woodchips including disposal of ash in a flow chart.

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[104] Cf. ROEDL, A. (2008), p. 9 et seq.
[105] Cf. BAUER, C. (2007), p. 37.
[106] Cf. BAUER, C. (2007), p. 18.
[107] Cf. BAUER, C. (2007), p. 19.
[108] Cf. BAUER, C. (2007), p. 62.

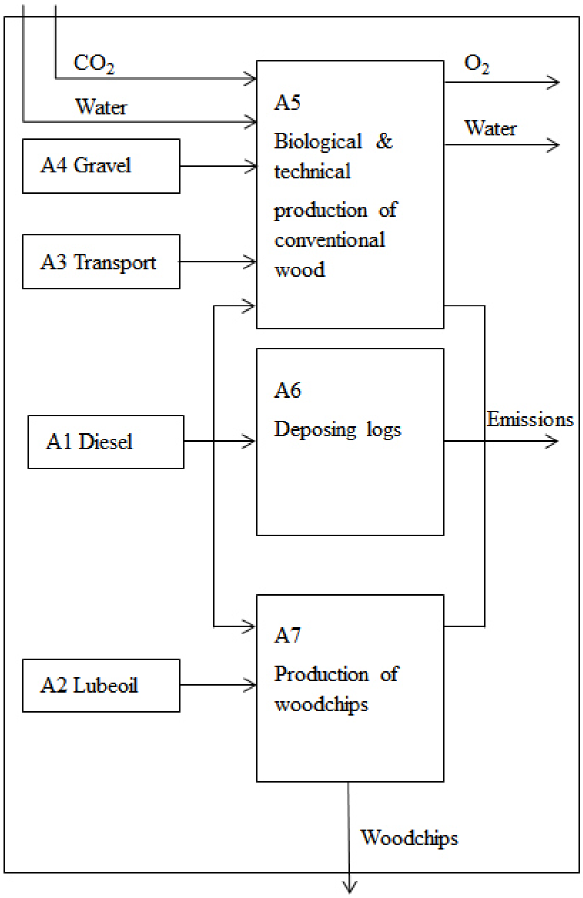

Figure 12: Production of woodchips - conventional forestry (Own illustration.)

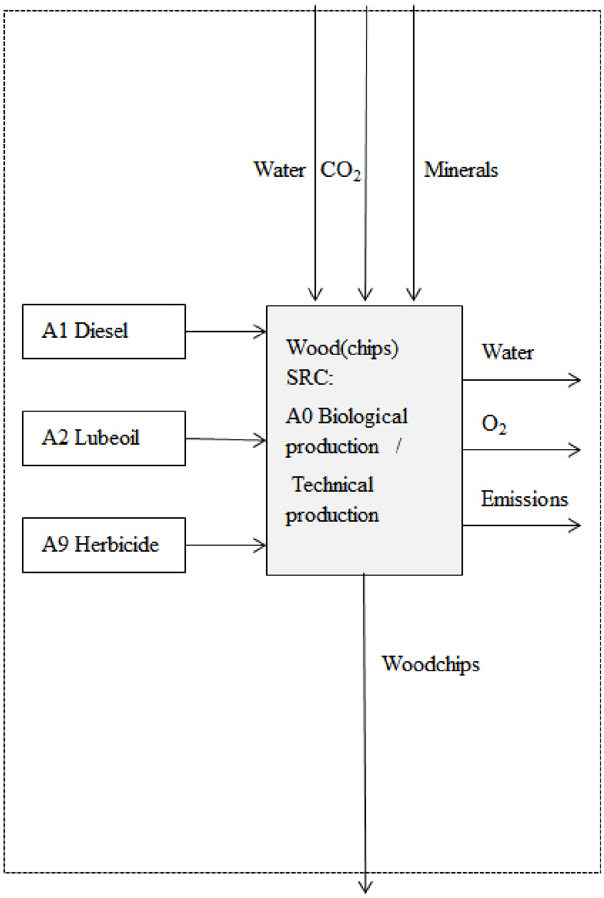

Figure 13: Production of woodchips – SRC (Own illustration.)

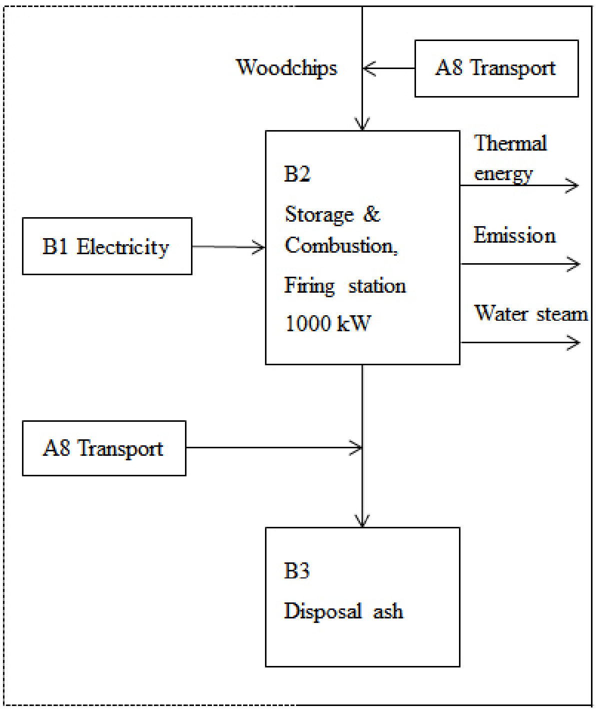

Figure 14: Combustion of woodchips – SRC & conventional forestry (Own illustration.)

Part 2: Manufacturing of Particleboard

Wood that is used for the production of particleboards has different sources.

For the board from conventional forestry, woodchips including small pieces of wood and waste wood as material for the interior layer as well as sawdust and shavings for the exterior layer is taken from sawmills and other wood industries. However, the main material for the internal layer is coming from conifer round wood. Additionally, there is a small amount of saw waste and dust arising from internal processes for the exterior layer.[109]

For the board from SRC, material for the interior layer is arising from wood of SRC (willow). Fine particles for the outside layers are taken from sawmill and other wood industries; like for the production of wood for particleboards from conventional forestry. There is a small amount of saw waste and dust arising from internal processes for the exterior layer, too.

Manufacturing particleboard from conventional forestry and SRC

There is general flow sheet for the production of particleboards consisting of: the subsystems of *wood preparation*, the subsystem of *board shaping* and the subsystem of *board finishing*. The subsystem of *wood preparation* starts with an outdoor storage of wood from the different sources described above. Subsequently, shaving machines and chippers shred the different wood materials into woodchips of a desired final particle size, which is important for the different layers of the board. Afterwards they are stored in different silos in terms of size and humidity. To ensure the three layer structure there is one silo for the storage and drying for fine particles of the outside layers and another silo of coarser particles for the inside layer. The drying process is implemented through direct contact with hot gas from natural gas burners. The subsystem of *board shaping* implements the resin mixing. This binder plays a key role in the stability of the final board. A commonly used resin is urea-formaldehyde. After the resin mixing long mats of each layer are formed separately by mixing the resin with the respective wood particles. Afterwards the preformed mats are transferred to the hot press for pressing and curing. Thereby an outside layer is laid down then a layer of coarse core particles is placed on top, forming the inside layer, followed by a second fine surface layer. As soon as heat reaches a temperature of 140–220ºC the glue curing process is pressing the board to the desired thickness. Accordingly, in the subsystem *board finishing*, hot boards are removed from the press to equilibrate moisture content and to stabilize. Subsequently the cooled boards get the desired thickness at the sander. At the sander the surface is treated and the cutting takes place according to the requirements. At the end waste cuttings and dust are reused at the chipper.[110]

Figure 15-19 respectively; illustrate the subsystem wood preparation and board shaping for both type of wood. The subsystem board finishing is equal for both woods.

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[109] Cf. RIVELA, B. et al. (2005), p. 107 et seq.
[110] Cf. RIVELA, B. et al. (2005), p. 107 et seq.

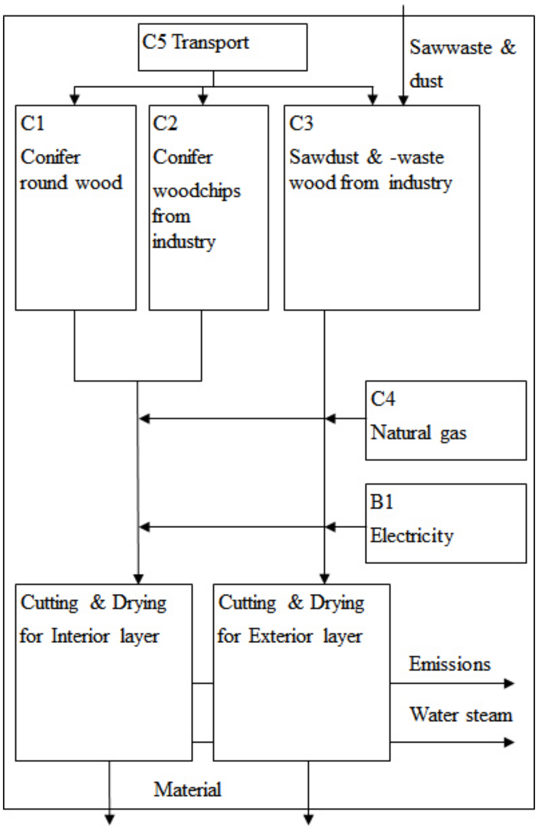

Figure 15: Wood preparation - conventional forestry (Own illustration.)

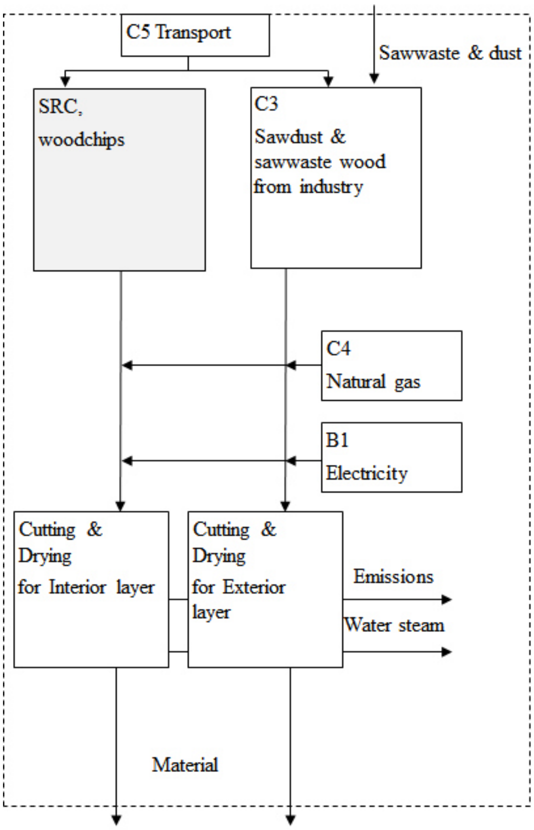

Figure 16: Wood preparation – SRC (Own illustration.)

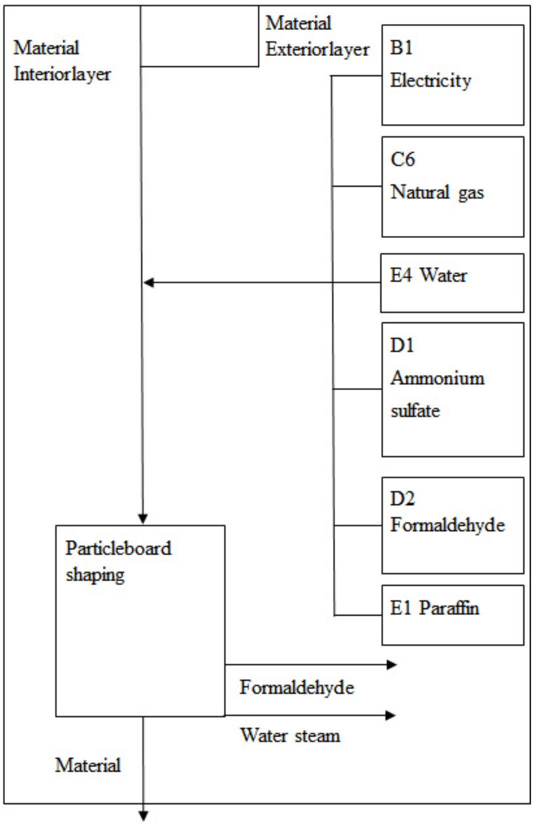

Figure 17: Board shaping - conventional forestry (Own illustration.)

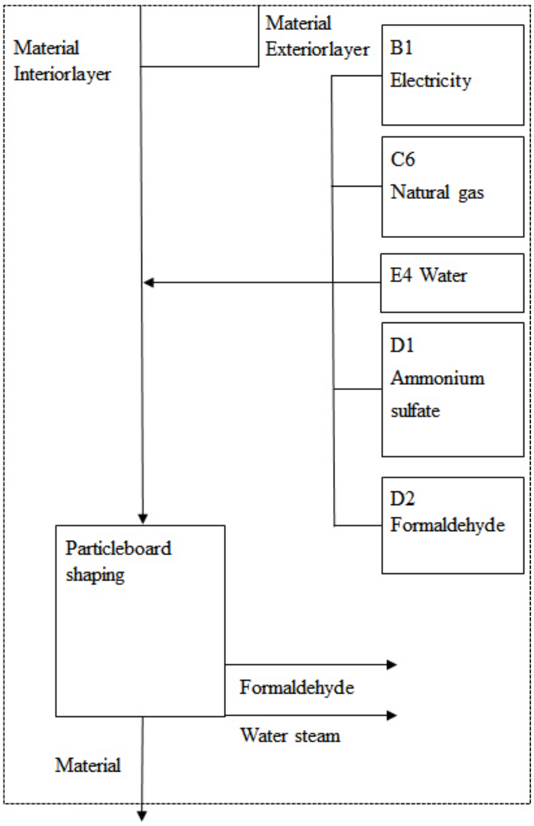

Figure 18: Board shaping – SRC (Own illustration.)

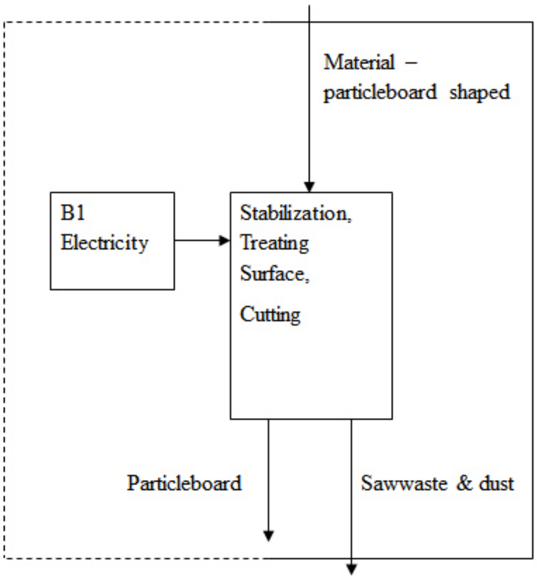

Figure 19: Board finishing - SRC & convetional forestry
(Own illustration.)

4.1.4 System Boundaries

Part 1: Energy Production

For both wood types the production of wood including biological and technical production of wood and woodchips respectively, is included in the present LCA study as well as the combustion of wood in a firing station. However, renewable energy in terms of solar radiation which initiates the build-up of tree biomass was not considered in the balance. It is assumed that the wood production and usage of both types of wood occurs in Central Europe. The final disposal of the wooden ash is included. Further components of the present LCA are transport activities, the use and production of fossil energy e.g. in terms of diesel – as well as the production and usage of operating materials e.g. lubricants. The usage of electricity from the grid is also included. Like in previous studie, the production and disposal of infrastructure e.g., machines for the production or the combustion of woodchips is not considered.[111] Due to uncertain or even unavailable data additional functions of forestry or SRC, like biodiversity, recreation or other social functions are not assessed.[112] Following previous studies, CO_2 uptakes in the soil or CO_2 emissions from the soil, especially for SRC, are not included.[113] The usage of the produced thermal energy is not relevant for a comparative LCA of wood and for this reason not considered. The system boundary for the energy production is shown in simplified terms in Figure 20.

[111] Cf. RIEZINGER, A. (2008), p. 11 et seq.; Cf. ROEDL, A. (2008), p. 20 et seq.
[112] Cf. RICHTER, K.; GUGERLI, H. (1996), p. 225 et seq.
[113] Cf. BURGER, F. (2010), p. 96.

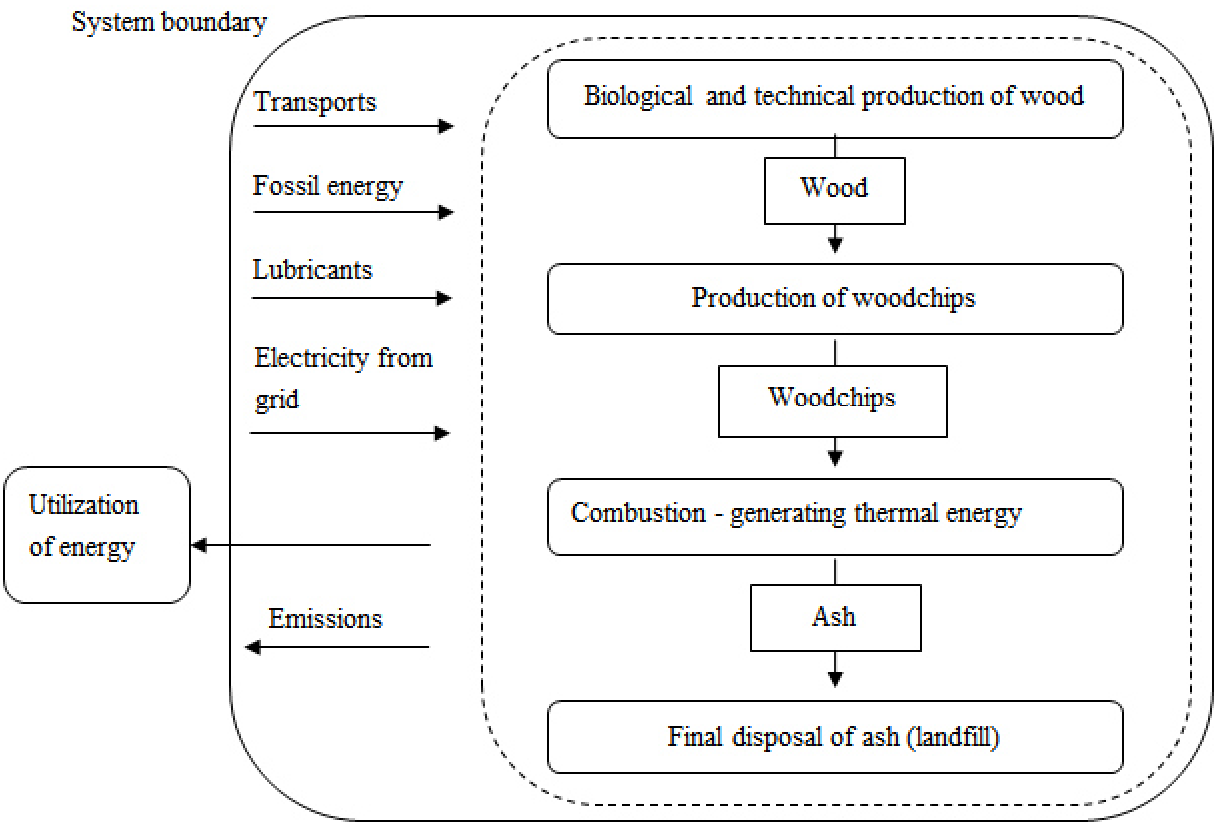

Figure 20: System boundary of energy production
(Own illustration.)

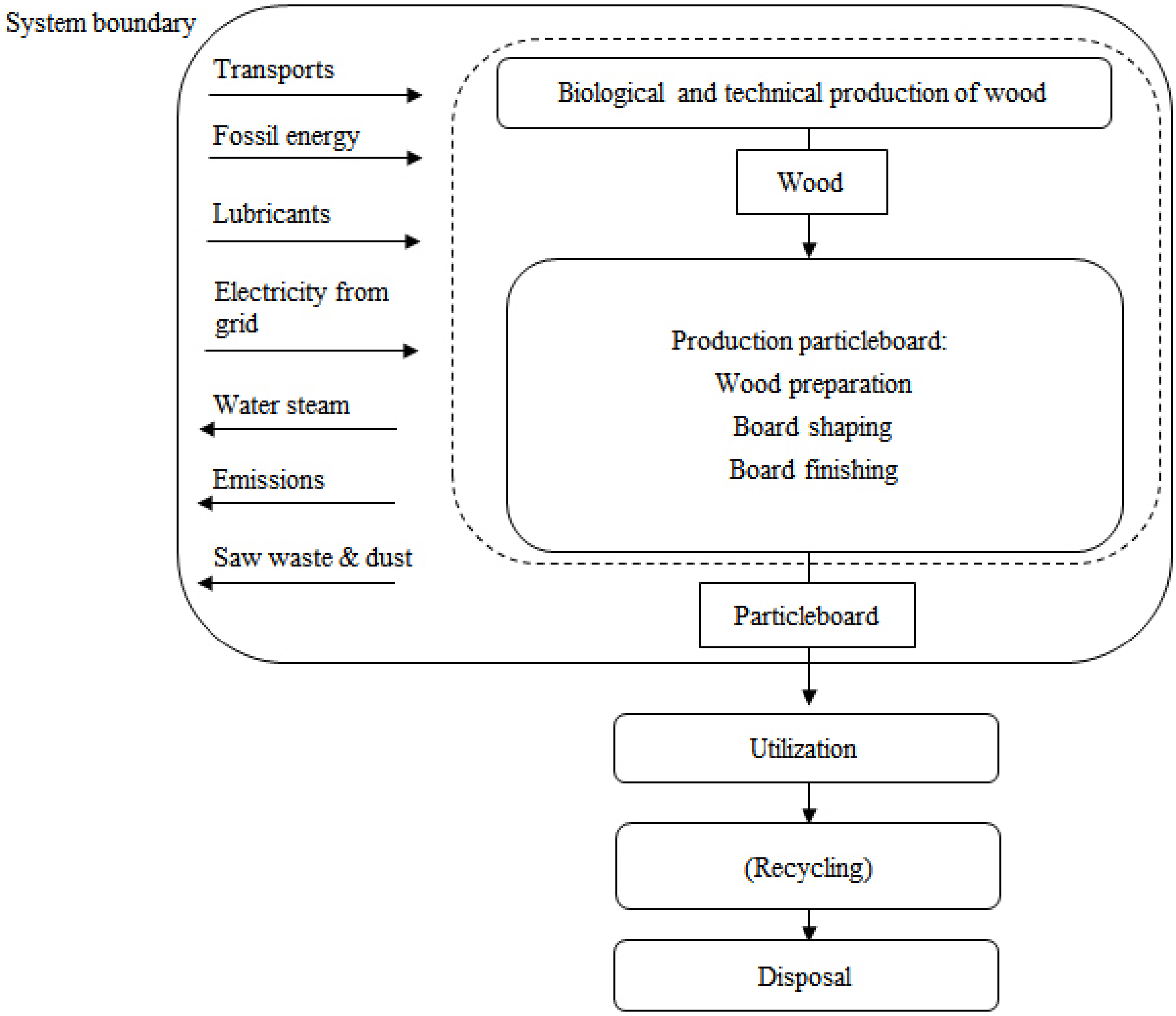

Figure 21: System boundary of particleboard production
(Own illustration.)

Part 2: Manufacturing Particleboard

For both types of wood the three subsystems wood preparation, board shaping and board finishing are included in the present LCA. The biological and technical production of wood as well as processes for the production of woodchips from industries and willow, round wood and sawdust are assessed. Similar to Part 1: transport activities, the production and usage of fossil energy, operating materials and electricity from grid are part of the LCA study. Infrastructure, additional functions of forestry or SRC and CO_2 uptakes or emissions in the soil are not considered. Renewable energy in form of solar radiation is not included. Because this part of the study is concentrating on the material usage of wood, the option using waste wood in a cogeneration plant for the production of energy and heat for subsystems of the particleboard production is not examined in the present study. Since particleboards made from SRC were just produced for technical purposes of research, there is no data applicable for further life cycle stages of the particleboard made from SRC.[114] Thus, for the comparison only the produc-

[114] Cf. WILCZYŃSKI, A. et al. (2011), p. 194.

tion of particleboard is examined. The system boundary for the manufacturing of a particleboard is shown in Figure 21.

4.1.5 LCIA Methodology

As shown in chapter 2.1, the state of the art recommends an assessment including a mid- and an endpoint approach. For the present study, the assessment is implemented with the Gabi 5 software using CML 2001 (version: "November 2010") as a midpoint oriented approach and Ecoindicator 99 (version: "Hierarchist Approach") defined for an endpoint oriented approach.[115] Both approaches comply with the requirements of the ISO standard.[116]

The impact assessment method **CML 2001**, is a set of categories that was developed by the Center of Environmental Science of Leiden University in the Netherlands.[117] "This method results in the definition of an environmental profile for the assessed product/process/service by quantifying the environmental effects on different categories, while only indirect or intermediate effects on humans can be assessed."[118] Different characterization categories exist, which are further described in GUINÉE, J. B. (2002).[119] However, for the present study four categories have been chosen to assess the environmental impacts of the production and combustion of biomass:

- Global warming potential (GWP) [kg CO2-Äqv.]
- Eutrophication potential (EP) [kg Phosphat-Äqv.]
- Acidification potential (AP) [kg SO2-Äqv.]
- Photo-oxidant creation potential (POCP) [kg Ethen-Äqv.]

According to the study of ROEDL, A. (2010), these are the most important categories for biomass cultivation and utilization.[120] Global warming is one of the most important issues facing humanity today. Emissions of gases, such as CO_2, nitrous oxide and methane caused by human society have lead to an unnatural warming, known as global warming. The potential impacts of having a high environmental level of macronutrients, nitrogen and phosphorus emissions into the air, water and soil are covered with eutrophication. Acidification is owing to the emission of acidifying substances, which causes negative effects in an ecosystem. Combined with other substances, sulphur dioxide and nitrogen oxides turn into acids and reach to the earth surface as rain or fog, with consequences for ground water and forestry. Photo-oxidant creation potential means that an increased level of ozone affects the ecosystem and human health. A high amount of nitrogen oxides and organic compounds leads to a high amount of ozone formed.[121]

For the natural gas used during the particleboard production the impact category

- Abiotic depletion for fossil resources (ADP f.) [MJ]

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[115] PE INTERNATIONAL (eds.) (2012), w.p.
[116] Cf. BRENT, A.; HIETKAMP, S. (2003), p. 28.
[117] Cf. FRISCHKNECHT, R.; JUNGBLUTH, N. (2007), p. 22.
[118] GONZÁLEZ-GARCÍA, S. et al. (2009), p. 460.
[119] Cf. GUINÉE, J. B. et al. (2001), p. 168 et seq.
[120] Cf. ROEDL, A. (2010), p. 568.
[121] Cf. GONZÁLEZ-GARCÍA, S. et al. (2009), p. 462.

is analyzed additionally. This category considers the use of fossil resources such as oil or gas.[122]

For the present study a normalization referring to the total environmental impact of each category in Europe (Europe 25) is chosen.[123]

The impact assessment method **Ecoindicator 99** gives information about the modification of the natural environment through emissions and expenditures of human activities. The method uses three conditions affecting human and environment. These conditions are referred to as endpoints, where damages through emissions and expenditures are perceived:

- Damage to ecosystem quality (EQ): the loss of species over a certain area, during a certain time expressed as potentially disappeared fraction of species due to an environmental impact.
- Damage to resources (R): expressed as the surplus of energy needed for future extractions of minerals and fossil fuels
- Damage to human health (HH): expressed as the number of years lost and the number of years lived disabled combined as Disability Adjusted Life Years (DALYs)[124]

Furthermore there are three archetypes of perspectives: the hierarchist, the individualist and the egalitarian perspective. They are representing the timeframe of the assessment.[125] Table 1 gives further information.

Table 1: Archetypes of perspective

	Time perspective	**Manageability**	**Required level of Evidence**
Hierarchist	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on Consensus
Individualist	Short time	Technology can avoid many problems	Only proven effects
Egalitarian	Very long term	Problems can lead to catastrophy	All possible effects

(Source: modified after GOEDKOOP, M. (2000), p. 7.)

It is recommended to use the hierarchist version with the option using the other versions as a sensitive analysis.[126] Characterization categories of the Ecoindicator 99 are:

- Human Health (HH):
    - Carcinogens [DALY]
    - Respiratory Ailments [DALY]
    - Climate Change [DALY]
    - Ozone layer depletion [DALY]

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122 Cf. GUINEE J. B. et al. (2001), p. 154.
123 PE INTERNATIONAL (eds.) (2012), w.p.
124 Cf. GOEDKOOP, M. et al. (2000), p. 13.
125 Cf. GOEDKOOP, M. et al. (2000), p. 2.
126 Cf. GUINEE et al. (2002), p. 532.

        - Radiation [DALY]
- Ecosystem quality (EQ):
    - Ecotoxicity [PDF*m^2*a]
    - Acidification / Eutrophication [PDF*m^2*a]
    - Land use [PDF*m^2*a]
    - Land modification [PDF*m^2*a]
- Resources (R):
    - Minerals [MJ surplus energy][127]

The normalization procedure of this method considers the total inventory of mass and energy used in Western Central Europe by one person per year. Moreover, a weighting procedure was carried out by a written panel procedure among a Swiss LCA interest group.[128]

Like described above, due to different valuation methods, results of Ecoindicator and CML must be interpreted disparate.

4.1.6 Data and Data Quality

The LCA is carried out to identify environmental burdens of processes of an energy and particleboard production in Central Europe. The present study uses most recent data available from literature and the Ecoinvent database[129]. Data for the production of wood from SRC was used from LCA studies of ROEDL, A. (2008) which analyzed the production of poplar; - GOGLIO, P.; OWENDE, P. (2009) and RÖHRICHT, C.; RUSCHER, K. (2009).[130] For the present study the production of willow is assumed for the analysis of the energetic and material usage of the same wood. Due to similar characteristic values and a high conformity of willow and poplar[131], data of the study of ROEDL, A. (2008) was not modified regarding the demand of energy and auxiliary materials for the production of wood from SRC.

For the production of a particleboard, data from an LCA study of RIVELA, B. et al. (2005) and WILCZYNSKI, A. et al. (2011) were chosen.[132] Both studies analyze pine wood for the production of the core layer of the particleboard. Due to a more precise data base and to enable analyzing the same wood for a material and energetic usage, spruce was chosen for the present study. Again, due to similar characteristic values, data of the studies of RIVELA, B. et al. (2005) and WILCZYNSKI, A. et al. (2011) were not modified for the present study regarding the demand of energy and auxiliary materials.

Data from the Ecoinvent database were used in order to specify processes for the production and combustion of conventional woodchips, for the production of conventional wood for particleboards as well as for all fossil- and auxiliary materials, transports and energies. Processes

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[127] PE INTERNATIONAL (eds.) (2012), w.p.
[128] Cf. BOVEA, M.D.; GALLARDO, A. (2006), p. 212.
[129] SWISS CENTRE FOR LIFE CYCLE INVENTORIES (eds.) (2012), w.p.
[130] Cf. ROEDL, A. (2008), p. 1.; Cf. GOGLIO, P.; OWENDE, P. (2009), p. 391.; Cf. ROEHRICHT, C.; RUSCHER, K. (2009), p. 23.
[131] Cf. GROSSER, D (2000), p. 1.
[132] Cf. RIVELA, B. et al. (2005), p. 106; Cf. WILCZYNSKI, A. et al. (2011), p. 194.

from Ecoinvent database for the production and combustion of wood were modified, to calculate without infrastructure; following previous studies.

As shown in chapter 2.1 data quality management with the pedigree matrix is most reasonable. It is illustrated in Appendix IX to describe data quality of the present study. Following WEIDEMA, B. P.; WESNEAS, M. S. (1996) the matrix should be seen in combination with information on the uncertainty of the data.[133] This step is not applied, due to a wide gap on information regarding uncertainty of the data.

As a result of the data quality assessment with the pedigree matrix it is shown, that regarding reliability especially processes of the production of woodchips from SRC and particleboard have a lower quality due to different assumptions. There is a good quality regarding the completeness and temporal correlation of the data. However, data for the production of the particleboards has to be improved for both quality indicators. Except the data for the production of SRC, there are very good results for the geographical correlation. Due to assumptions for the production and combustion of wood from SRC and the production of the particleboard, there is a poor result for the technological correlation for these processes. However, production and combustion of conventional wood have a high quality for the technological correlation. It is obvious, that mostly data quality of SRC and particleboard production is critical. However, there is no LCA study existing for a particleboard from SRC and a comparison between the two types of wood. The present study represents a first attempt for an LCA for particleboard from SRC without on-site measurement. Furthermore, due to carefully chosen and well-founded explanations of the assumptions and no possibility for on-site measurements the data quality is considered as sufficient for the LCA analysis.

4.1.7 Allocation

Allocation is defined as the division of input and output flows of a unit process to the production system. That means that environmental aspects are allocated to different products or product systems. Generic processes for allocations are:

- Multi output processes: e.g. sawn timber and sawdust from saw mill
- Multi input processes: e.g. allocation of energy or emissions to the combustion of different types of wood
- Recycling

Two allocation problems for wood can be identified: the close relation between material and energetic usage together with the generation of various byproducts in the production process. There are different solutions for the treatment of allocations in LCA of wood based products. Different allocation procedures can have a significant influence on the results of LCA of wood products. JUNGMEIER, G. et al. (2002) outline a step wise procedure dealing with allocation problems:

[133] Cf. WEIDEMA, B. P.; WESNEAS, M. S. (1996), p. 169 et seq.

1. Avoiding allocation by system expansion: including energy production or a further processing from byproducts when they originate during the production.
2. Avoiding allocation by substitution: e.g. if bioenergy is used for the production process, the process of the fossil energy supply can be given as credit to the wooden product.
3. Allocation of unit processes: to deal with the multi-functionality problem of LCA it is possible to allocate unit processes to the various products.
4. Different allocation options should be analyzed with the help of a sensitive analysis.
5. The same LCA can include different allocation factors e.g. mass or quantity.
6. Most practical allocations for forestry are allocations based on mass or volume and for wooden industry an allocation based on mass or market price.[134] Whereby market prices should not be preferred through their volatile variation over time.[135]

In the present study, a multi output process exists, producing the particleboard as the main product and sand down dust as a byproduct. Following JUNGMEIER, G. et al. (2002) an allocation was avoided in the present study. There is an intern utilization of sand down dust as an input of the wood preparation system of the particleboard production. Furthermore, industrial woodchips for particleboard production and wood residues from round wood for the combustion of conventional woodchips are byproducts from industrial processes and round wood production, respectively.

Allocation procedures and data of these byproducts are adopted from the Ecoinvent database.[136] Data for the different input material for particleboard production is adopted from RIVELA, B. et al. (2005).[137]

4.2 Life Cycle Inventory

This chapter specifies the life cycle inventories for the scenarios. It is structured according to chapter 4.1.3; the “Product System”. The values obtained for the unit processes are altered to reflect the functional unit. Main in- and outputs are illustrated in the following inventory tables. Additionally, all processes used from the Ecoinvent database, are shown in the flow charts of the product system, chapter 4.1.3. They are denoted with capitals and a number (e.g.: A1). These marks can be found in Appendix VI, where further information like “Indexnumber”, “Name of the process”, and “Source of data”, “Time-” and “Geographical information” is attached. This information was obtained from the “Dataset information” of the respective process from Ecoinvent database. Again, several characteristics of wood and calculations are attached in Appendix V and XI.

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[134] Cf. JUNGMEIER, G. et al. (2002), p. 290 et seq.
[135] Cf. RIVELA, B. et al. (2005), p. 106.
[136] Cf. SWISS CENTRE FOR LIFE CYCLE INVENTORIES (eds.) (2012), w.p
[137] Cf. RIVELA, B. et al. (2005), p. 109

4.2.1 Part 1: Energy Production

Production of woodchips from conventional forestry

The production of woodchips from conventional forestry was computed with the Gabi software. Data was taken from Ecoinvent database.

Table 2: Production of woodchips from conventional forestry

Input			
From system		**From environment**	
Materials	**kg**	**Substances**	**kg**
Gravel	7,0*E-3	Water	5,0*E-3
Conifer Wood	4,35*E-5	CO_2	1,0*E-1
Lube oil	4,58*E-7	…	
Energy	MJ		
Diesel	1,4*E-3		
Transport	tkm		
Forestry	3,3*E-3		
Output			
To system		**To environment**	
Materials for combustion	**m^3**	**Emissions to air**	**kg**
Woodchips	3,33*E-4	CO	1,2*E-6
		CO_2	3,5*E-5
		…	

(Own illustration.)

Production of woodchips from SRC

ROEDL, A (2008) computed the production of 1000 kg (bd) woodchips with a total diesel consumption of 92,1 MJ.[138] The biological production was calculated according the photosynthesis equation shown above.

Further substances taken from environment for biological production are used from BOELKE, B. (2006).[139] The amount of lube oil was calculated according to the study of GOGLIO, P.; OWENDE, P. (2009).[140] The amount of herbicide is computed regarding the study of RÖHRICHT, C.; RUSCHER, K. (2009).[141] The area used for SRC is calculated according to BOELKE, B. (2006): for one ton of woodchips an area of 1000 m^2 is needed.[142] Processes were taken from Ecoinvent.

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138 Cf. ROEDL, A. (2008), p. 17.
139 Cf. BOELKE, B. (2006), p. 11 et seq.
140 Cf. GOGLIO, P.; OWENDE, P. (2009), p. 391.
141 Cf. ROEHRICHT, C.; RUSCHER, K. (2009), p. 23.
142 Cf. BOELKE, B. (2006), p. 11.

Table 3: Production of woodchips from SRC

Input			
From system		**From environment**	
Energy	**MJ**	**Substances**	**kg**
Diesel	4,7*E-3	Water	1,0*E-1
		CO_2	8,5*E-2
Material	**kg**	Calcium	2,7*E-4
Lube oil	3,58*E-6	Magnesium	4,0*E-5
Herbicide	3,45*E-6	Potassium	1,3*E-4
		Azote	1,8*E-4
Output			
To system		**To environment**	
Materials for combustion	**m^3**	**Substances**	**kg**
Woodchips	$3{,}33{*}E^{-4}$	O_2	6,4*E-2
		Water	2,0*E-2
		CO_2	4,1*E-4
		…	

(Own illustration.)

Combustion of woodchips

As shown above, because of a very similar combustion process for both types of woodchips, the combustion is calculated with the same data of the Ecoinvent database.

The transport of ash which is deposited on a landfill was stated through the Gabi software and the Ecoinvent process, respectively. The Ecoinvent process “B2 - furnace, wood chips, softwood, 1000kW” proposes three different ways for the disposal of ash. Because of, arising ash of industrial firing systems usually gets deposited on a landfill[143], the other two disposal methods (“Landfarming”, “Refuse combustion”) are not considered. Furthermore, a transport distance of 30 km is adopted which is an average transport distance from wood production to consumer.[144]

[143] Cf. BAUER, C. (2007), p. 62.
[144] Cf. BAUER, C. (2007), p. 32.

Table 4: Combustion of woodchips from conventional forestry and SRC

Input			
From system			
Materials	**m^3**	**Energy**	**MJ**
Woodchips	3,33*E-4	From grid	1,5*E-2
		Transport	**tkm**
		Firing system to landfill	4,05*E-3
		Plantation to consumer	3,3*E-3
Output			
To system		**To environment**	
Energy	**MJ**	**Emission**	**kg**
Thermal energy	1	CO_2	1,0*E-1
		Dust	9,16*E-6
Materials from combustion	**kg**	Magnesium	3,60*E-07
Ash	$4{,}76{*}E^{-4}$	…	

(Own illustration.)

4.2.2 Part 2: Manufacturing Particleboard

Manufacturing particleboard from conventional forestry

Since analyzing the material usage – and not the energetic utilization - of wood is considered in this part of the study, the LCI data of RIVELA, B. et al. (2005) has to be modified: The usage of wooden materials and bark for the combustion in a cogeneration plant was not assessed. Instead, round wood without bark was considered; energy from the cogeneration plant was substituted with energy coming from natural gas or grid. Usually the weight of bark, which is not used for the cogeneration plant, has to be subtracted. Due to a lack of data regarding weight, moisture content and density of the bark and to avoid wrong assumptions, bark is not subtracted. This is equal for both types of wood. The co-product “Sand-down dust“ arising from the board finishing process is used as fine particles for the exterior layer. For this reason it is subtracted from the needed saw dust. No valid data could be found for assessing “Edgings” in the wood preparation process. For this reason, the amount of 125,57 kg is assumed as woodchips. Due to the size and the industrial background of these wooden materials this seems to be most appropriate. “Sawdust” is assessed with the Ecoinvent process: “sawdust, Scandinavian softwood (plant-debarked), u=70%, at plant”. Moreover, for the calculation with Gabi the unit [kg] has to be converted in [m^3] for the wooden inputs coming from the external system. It is assumed that wood is coming from Central Europe. Thus, no sea ship transport is considered. Like for the other processes, the calculation of the infrastructure is excluded. Table 5-7 show LCIs of the particleboard production of conventional forestry.

Table 5: Subsystem wood preparation – conventional forestry

Input			
From system			
Materials	**kg**	**Energy**	**MJ**
Round wood	892,82	Electricity for machine	
Saw waste	36,76	Grid	151,20
Woodchips	166,15	Drier Exterior Layer	
Sawdust	203,35	Natural Gas	1037,20
Sand down dust	53,68	Drier Interior Layer	
		Natural Gas	2074,41
		Transport	**tkm**
		Truck	110,96
Output			
To system		**To environment**	
Materials for board shaping	**kg**	**Emissions to air**	**kg**
Chips and shavings (int. layer)	444,09	CO_2	267
Shavings and sawdust (ext. layer)	222,04	Water steam	561,98
		…	

(Source: modified after: RIVELA, B. et al. (2005), p. 110)

Table 6: Subsystem board shaping – conventional forestry

Input			
From system		**From environment**	
Materials for board shaping	**kg**	**Raw materials**	**kg**
Chips and shavings (int. layer)	444,09	Water	19,69
Schavings and sawdust (ext. layer)	222,04		
UF-Resin	67,94		
Paraffin	2,13		
Ammonium sulphate	0,74		
Energy	**MJ**		
Natural gas	724,49		
Electricity for machine	37,8		
Output			
To system		**To environment**	
Materials	**kg**	**Emissions to air**	**kg**
Particleboard shaped	730,44	Water steam	14,98
		Formaldehyde	0,06
		CO_2	76,9
		…	

(Source: modified after: RIVELA, B. et al. (2005), p. 110)

Table 7: Subsystem board finishing – conventional forestry

Input	
From system	
Materials for board shaping	**kg**
Particleboard shaped	730,44
Energy	**MJ**
Electricity for machine	
Grid	189
Output	
To system	
Product	**Volume**
Board finished	1 m^3
Waste to recycle	**kg**
Waste from sawdust	36,76
Sand down dust	53,68

(Source: modified after: RIVELA, B. et al. (2005), p. 110)

Manufacturing particleboard from SRC

Due to equal processes for the manufacturing of a particleboard from SRC, the same quantities of energy, transports are assumed as for conventional wood. However, there are different inputs for wood and lubricants for the subsystem of wood preparation and board shaping, which are shown in the following tables. Wood for the interior layer is substituted with woodchips from willow. The same amount of sawdust for the exterior layer is assumed. As described above, there is saw waste and dust arising from the board finishing subsystem and used in the wood preparation subsystem. Moreover, as shown in the study of WILCZYNSKI, A. et al. (2011) there is no paraffin wax as hydrophobic agent used in the board shaping subsystem.[145] The differences of the input materials are shown in Table 8 and 9.

Table 8: Inputs for wood preperation - SRC

Input	
From system	
Materials	**kg**
Sawdust	203,35
Sand down dust	53,68
Saw waste	36,76
Woodchips (SRC)	1058,97

(Own illustration.)

[145] Cf. WILCZYNSKI, A. et al. (2011), p. 195.

Table 9: Inputs for board shaping - SRC

Input	
From system	
Materials for board shaping	**kg**
Chips and shavings (int. layer)	444,09
Schavings and sawdust (ext. layer)	222,04
UF-Resin	67,94
Ammonium sulphate	0,74

(Own illustration.)

4.3 Life Cycle Impact Assessment and Interpretation

Below, the LCIA and the interpretation of the data are implemented. Afterwards results of the sensitivity analysis are presented. Only a selection of figures is displayed. Graphics depict the characterized and comparative illustration of the data for CML 2001 and Ecoindicator, respectively. Further data and illustrations of normalized data of the compared products is attached in Appendix X. For a direct comparison of the two wood types, “woodchips from SRC” is chosen as basis scenario and is therefore set to 100%.

4.3.1 Part 1: Energy Production

As described above, the comparison is focused on the production of woodchips; the combustion is shown with the example of the combustion of conventional wood.

CML 2001

Production of woodchips from conventional forestry

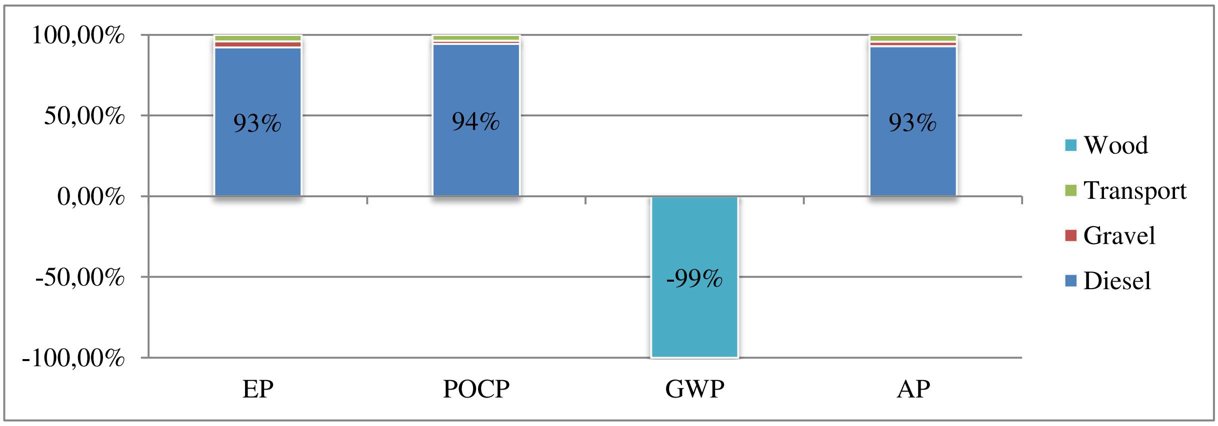

Figure 22: Impact assessment woodchips of conventional forestry, Characterization, CML
(Own illustration.)

Figure 22 illustrates the diesel consumption of forest and harvest machines, during the technical production of wood and the harvest itself that exhibits a high contribution for EP, POCP and AP. In consequence of the CO_2 uptake during the biological production of wood (illustrated with “Wood”), there is a negative amount for GWP (-99%). Diesel has a small impact on GWP. Lube oil, transports within forestry and gravel used for cultivation processes of trees, have little to no effect on the impact categories(< 5%). The biological production of wood has no effect on EP, POCP and AP. From an environmental point of view, it is the only component with a “positive” influence to nature regarding CML.

Production of woodchips from SRC

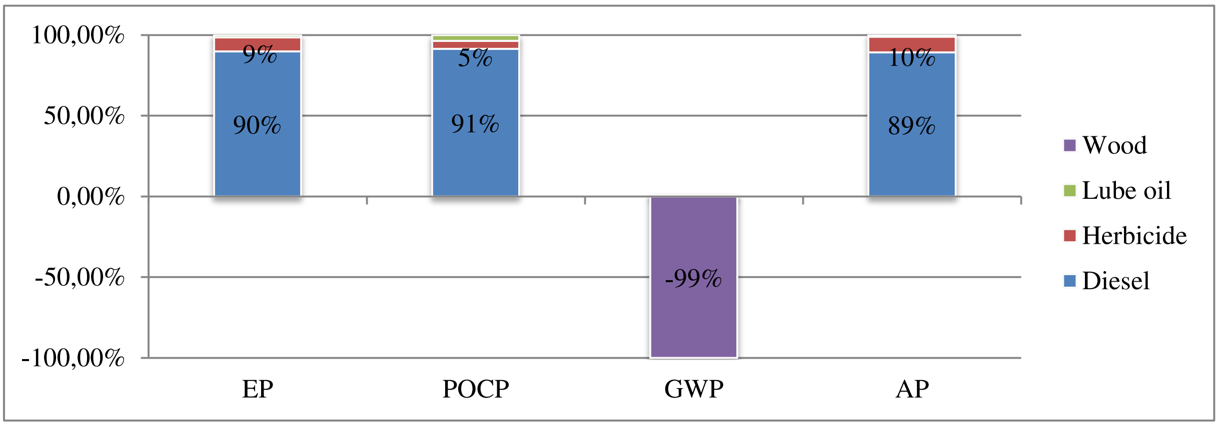

Figure 23: Impact assessment woodchips of SRC, Characterization, CML (Own illustration.)

Figure 23 shows, that there is almost the same picture for the production of woodchips from SRC. Diesel for construction machines used for the technical production of woodchips is the greatest contributor to EP, POCP and AP. Again, there is a negative value for GWP through the biological production of wood. Lube oil, has little to no effect on the impact categories (< 5%). Herbicides have moderate impacts on EP, AP and low ones on POCP and GWP.

Comparison of woodchips from conventional forestry and SRC

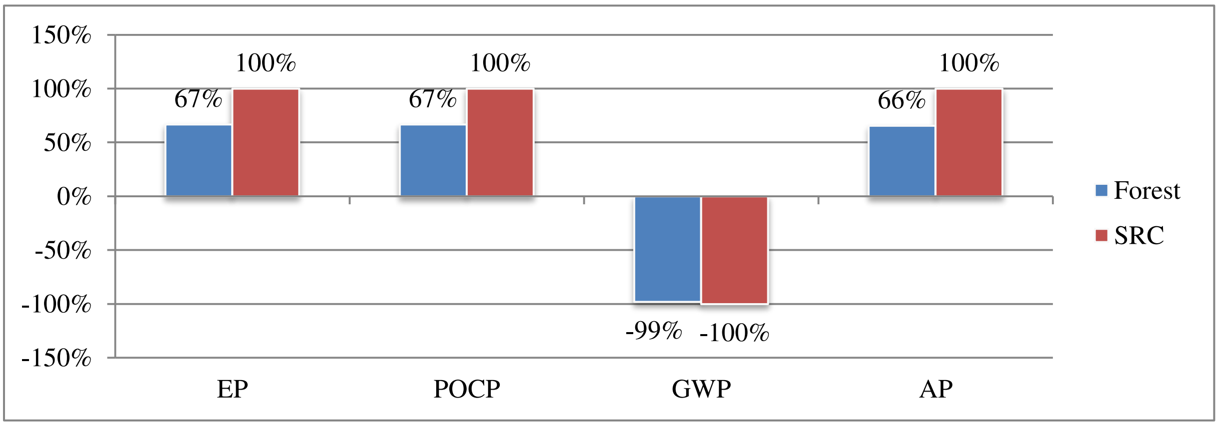

Figure 24: Comparative impact assessment woodchips, Characterization, CML (Own illustration.)

Differences between the two possibilities of wood production are elucidated in Figure 24. Except for GWP, where values of woodchips from forestry and SRC are almost equal, woodchips from conventional forestry have lower impact on EP, POCP and AP. As shown above, diesel is the greatest contributor to these categories. Additionally herbicides are used. Thus, higher diesel consumption plus herbicides during the technical production of woodchips from SRC is responsible for worse values than chips from forestry. However, normalized absolute values of both types of woodchips show that they both have a great impact on GWP. Despite of higher values for SRC, both have a minimal influence on EP, POCP and AP.

Combustion of woodchips

As shown in Figure 25, there is a different scenario for the combustion of woodchips. Due to releasing substances during the combustion process like phosphate-, ethen-, CO_2- and SO_2-equivalents it can be seen, that the combustion presents the highest contribution to all categories. Beside the combustion, electricity from grid used for machines at the firing system has a high impact on EP and lower impact on POCP, GWP and AP. The combustion releases CO_2 bounded during the biological production of wood, which results in a high positive value for GWP (96%). Due to transports from wood production side to firing system, transport has a moderate impact on EP, POCP and AP. Disposal has almost no influence on impact categories. (< 3%).

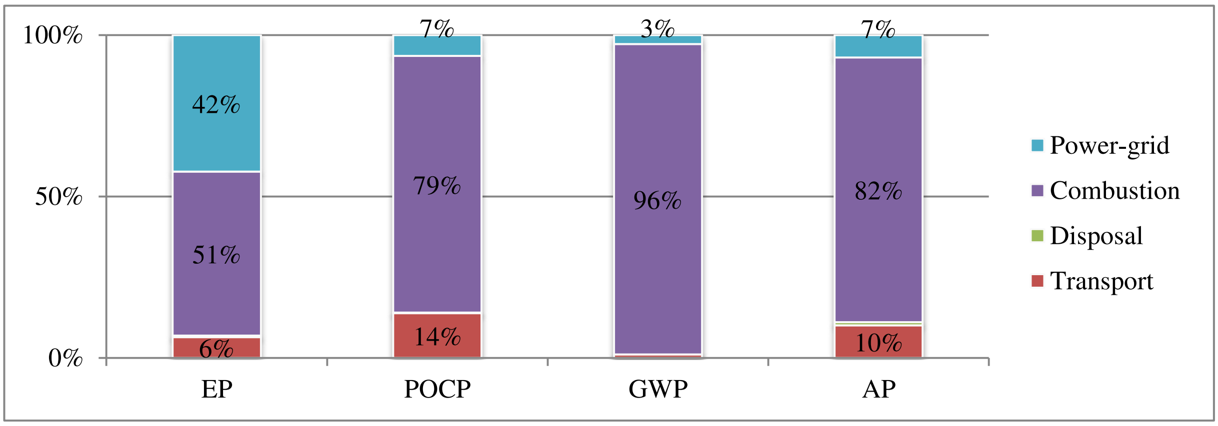

Figure 25: Impact assessment combustion of woodchips, Characterization, CML (Own illustration.)

Normalization shows, that due to releasing emissions, mainly CO_2, during the combustion process of woodchips; the production of thermal energy has the highest impact on GWP, low to moderate influence on AP, EP and a low impact on POCP.

Ecoindicator 99

Production of woodchips from conventional forestry

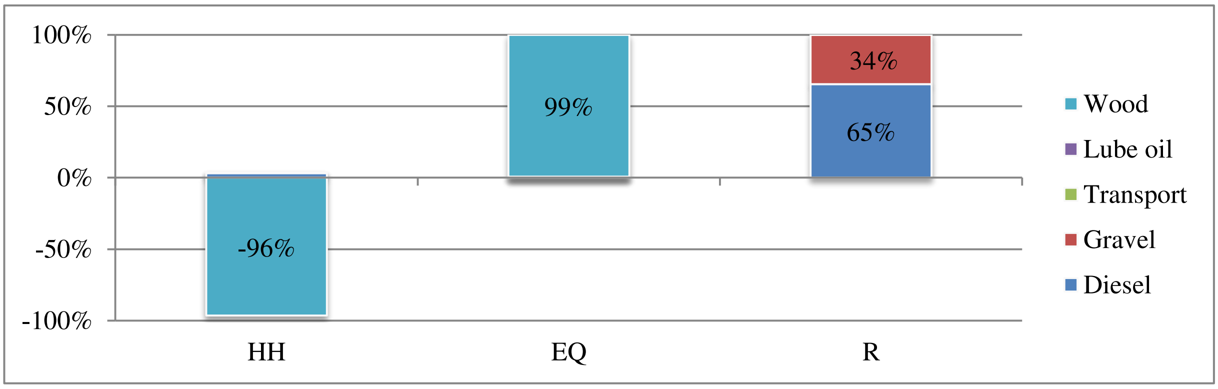

Figure 26: Impact assessment woodchips of conventional forestry, Characterization, EI99 (Own illustration.)

As displayed in Figure 26, the high impact of the biological production of wood ("Wood") on HH and EQ is conspicuous. HH considers the impacts of climate change. Due to the CO_2 uptake there is a negative value of 96%. EQ considers the impacts of land use and the associated modification of unspoiled areas. Due to the economic usage of the forest, the cultivation of trees for the production of wood is the highest contributor to EQ with 99%. Due to R includes the consumption of minerals and fossil fuels, it is shown, that the diesel consumption of forest machines presents the highest contribution to R followed by gravel. Due to small quantities during production process, transport and lube oil have little to no effects to HH, EQ and R (< 5%).

Production of woodchips from SRC

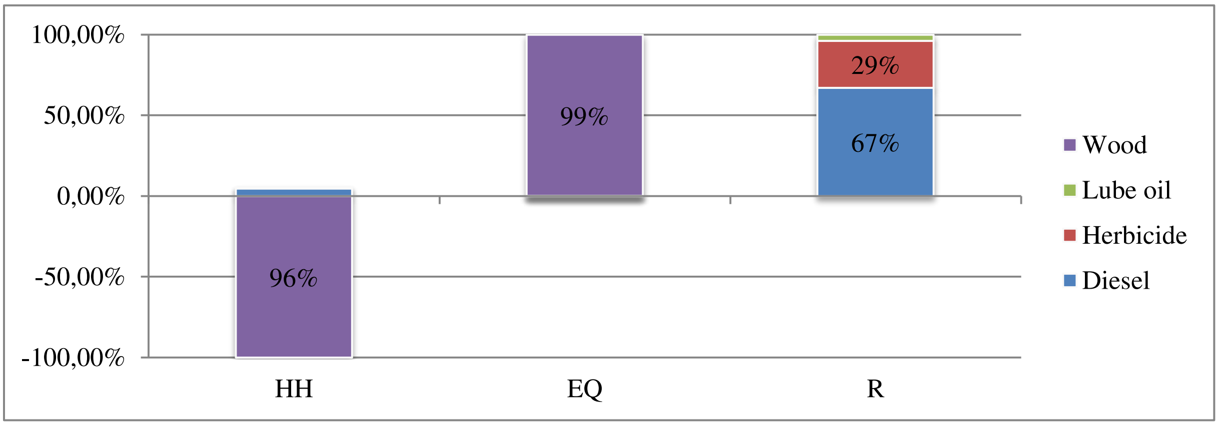

Figure 27: Impact assessment woodchips of SRC, Characterization, EI99
(Own illustration.)

Again, because both times the production of wood is assessed, there is almost the same picture (Figure 27) for the production of woodchips from SRC: The CO_2 uptake during the biological production results into a negative value for HH (96%). The diesel consumption is a small contributor to HH. Approximately 99% of the contribution to EQ is associated with land use and modification for the cultivation of the short rotation trees on agriculture areas. Herbicide accounts for 29 % and diesel for 67% of the total contribution to R, due to a consumption of minerals for herbicides and fossil fuels for diesel. Again, lube oil has little to no effects on HH, EQ and R (< 5%).

Comparison of woodchips from conventional forestry and SRC

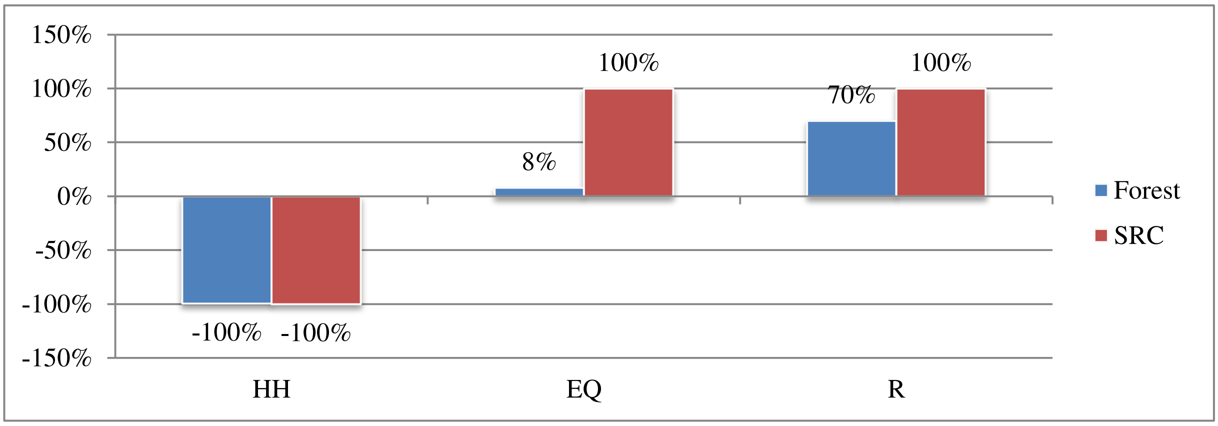

Figure 28: Comparative impact assessment woodchips, Characterization, EI99
(Own illustration.)

The direct comparison which is illustrated in Figure 28 shows, that woodchips from SRC obtain higher positive values for EQ and R and an equal value for HH. There is a large difference on EQ and a moderate difference on R. As shown above, this is associated with a higher land use and modification, a higher consumption of diesel as well as the usage of herbicides for SRC, respectively. Normalized absolute values indicate that the production of woodchips has a high negative impact on HH, and very low impact on R. However, due to substantial land use, SRC has large influence on EQ, whereas forestry has a comparatively low one.

Combustion of woodchips

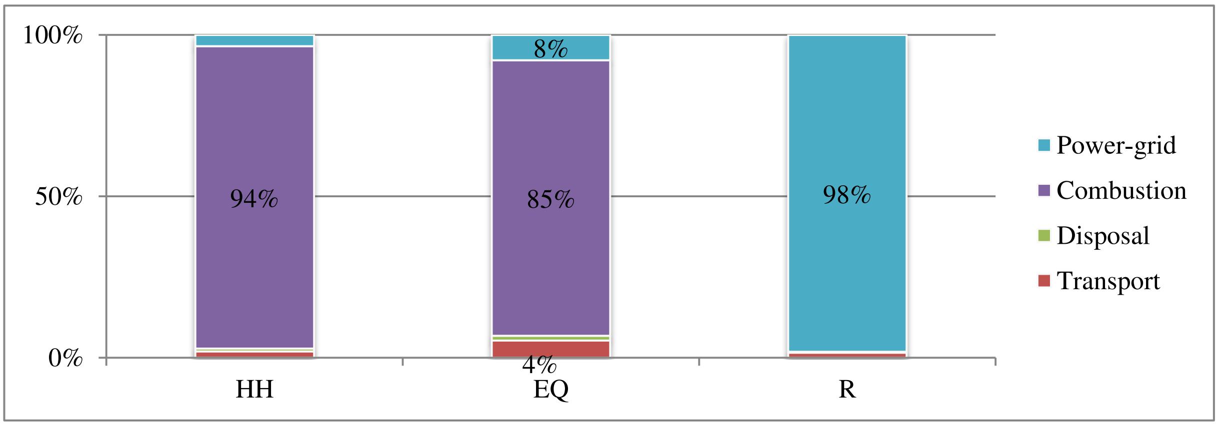

Figure 29: Impact assessment combustion of woodchips, Characterization, EI99
(Own illustration.)

As displayed in Figure 29, emissions during the combustion process make the combustion of wood the main contributor to HH and EQ. The high value for HH occurs through the released emissions in the air. The released CO_2 influences climate change and with that HH. The great value for HH further occurs through emissions such as dust particles which have a great impact on respiratory ailments. Beside the land use, EQ also considers ecotoxicity and acidification which both have a high value for the combustion process. Power/ electricity from the grid represent 98% of the total contribution to R, 8% to EQ and 2% to HH. With respect to electricity a power mix was chosen which also uses fossil fuels for energy production. This leads to consumption of resources and with that to a high value on R. Disposal and Transport are not determining for values on HH, EQ and R (< 5%). Normalized absolute values for the combustion show, that through releasing emissions, combustion has the largest impact on HH and a moderate effect on EQ and a small one on R.

4.3.2 Part 2: Manufacturing Particleboard

CML 2001

Manufacturing particleboard from conventional forestry

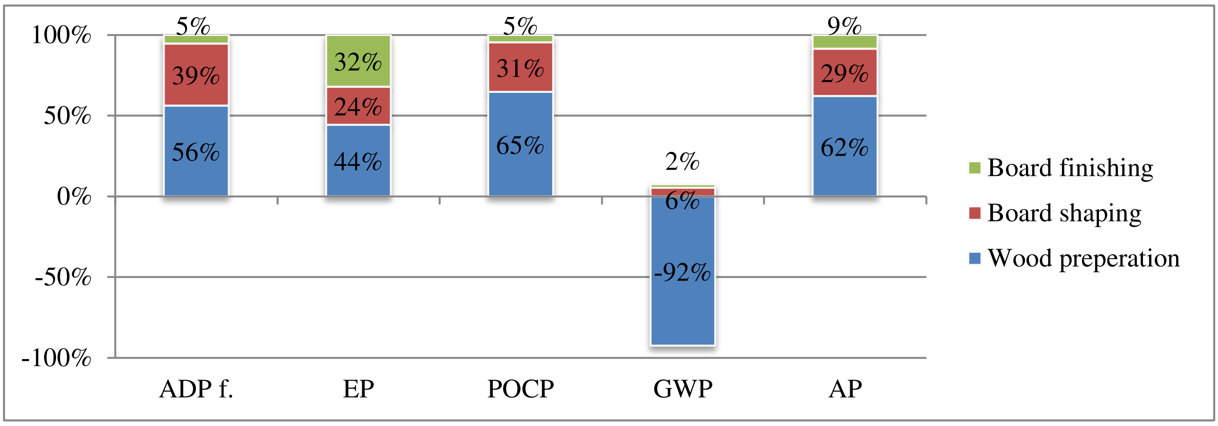

Figure 30: Impact assessment particleboard, conventional forestry, Characterization, CML (Own illustration.)

Figure 30 reveals, that wood preparation is the greatest contributor to all impact categories, mainly due to the required natural gas and electricity for machines. Again, there is a negative value for GWP through the CO_2 uptake during wood production (-92%). Mainly caused by the UF-resin and natural gas, the board shaping subsystem is the second largest contributor to ADP f., POCP, GWP and AP. Due to the large electricity consumption, the board finishing subsystem is the second largest contributor to EP. However, it has low to moderate values for ADP f., POCP and AP. Board finishing and -shaping subsystems have almost no influence on GWP.

Manufacturing particleboard from SRC

For the same reasons as for conventional wood, there is approximately the same picture for the particleboard from SRC illustrated in Figure 31. Again, wood preparation is the largest contributor to all categories with a negative value for GWP. The board shaping subsystem is the second largest contributor to ADP f., POCP, GWP and AP. Board finishing is the second largest contributor to EP but has small to moderate influence on ADP f., POCP and AP. Again, board finishing and -shaping subsystem have almost no influence on GWP.

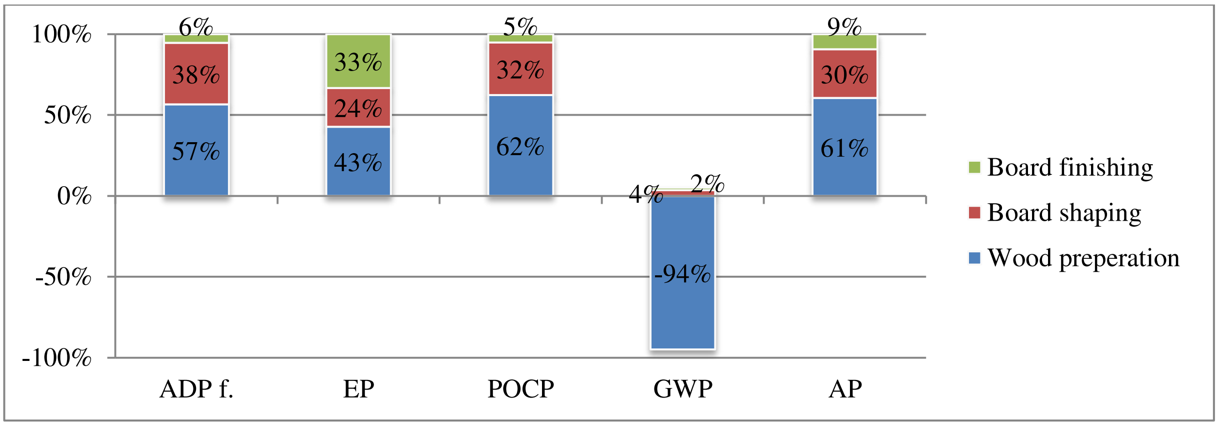

Figure 31: Impact assessment particleboard, SRC, Characterization, CML
(Own illustration.)

Comparison of particleboards from conventional forestry and SRC

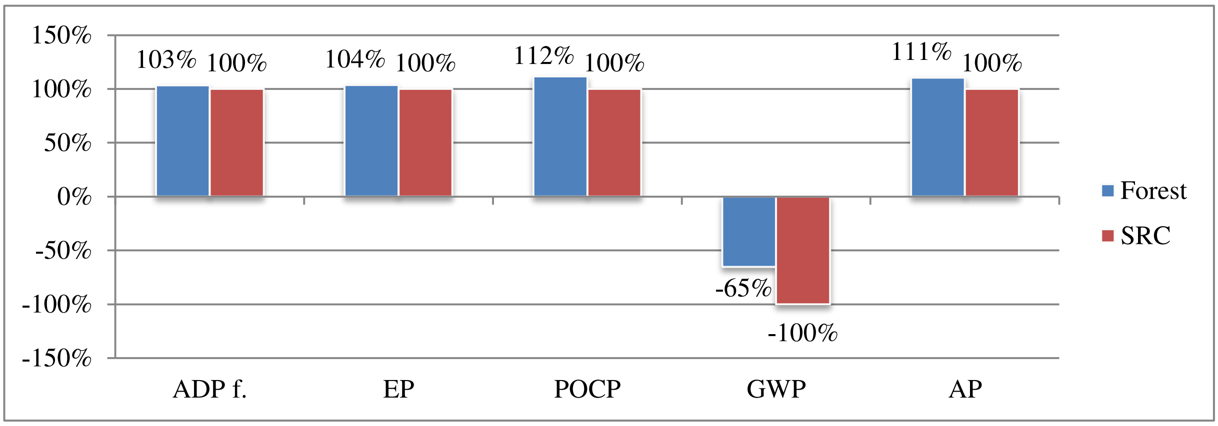

Figure 32: Comparative impact assessment particleboard, Characterization, CML
(Own illustration.)

Despite the similarity of the characterized values shown above, the direct comparison in Figure 32 shows, that the production of the particleboard from conventional forestry has higher values for ADP f., EP, POCP, AP and a lower negative value for GWP. Due to equal quantities for energy consumption and materials for exterior layer for both particleboards, materials of the interior layer and the additional paraffin wax are responsible for higher values of conventional forestry. Normalization shows that the particleboard production has large impact on ADP f., through the consumption of natural gas; and GWP through the CO_2 storage in wooden products.

Ecoindicator 99

Manufacturing particleboard from conventional forestry

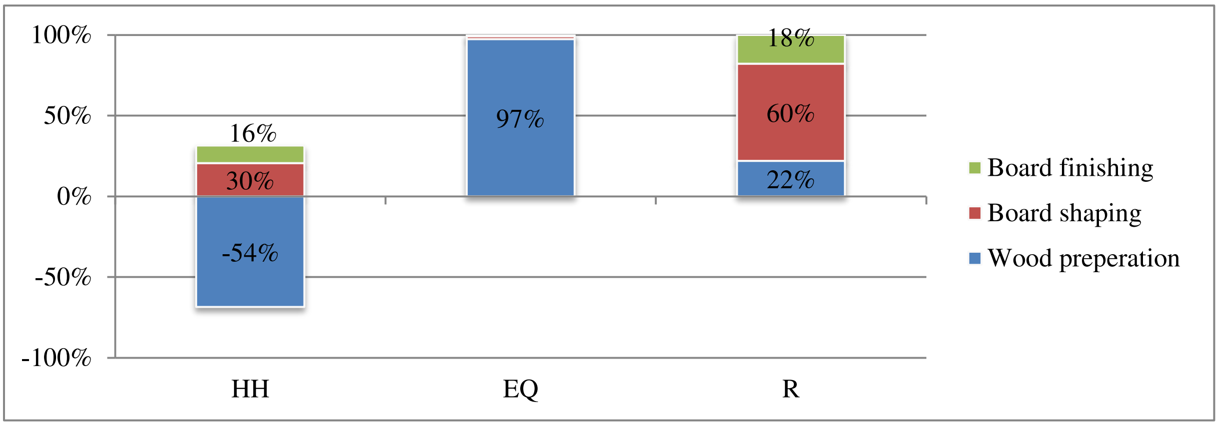

Figure 33: Impact assessment particleboard, conventional forestry, Characterization, EI99 (Own illustration.)

As depicted in Figure 33, for the Ecoindicator, the wood preparation subsystem has the greatest impact on HH and EQ. Again the CO_2 storage is responsible for the negative value on HH, the land use during the wood production and as a component of the wood preparation subsystem is the greatest contributor to EQ. The usage of the UF-resin is responsible for the moderate value of board shaping on HH and the high value on R. There are moderate values for the board finishing subsystem on R and HH and for the wood preparation subsystem on R. This is a result of the large electricity consumption from the power mix and the usage of natural gas, respectively. Moreover, board finishing and – shaping have small impacts on EQ (< 3%).

Manufacturing particleboard from SRC

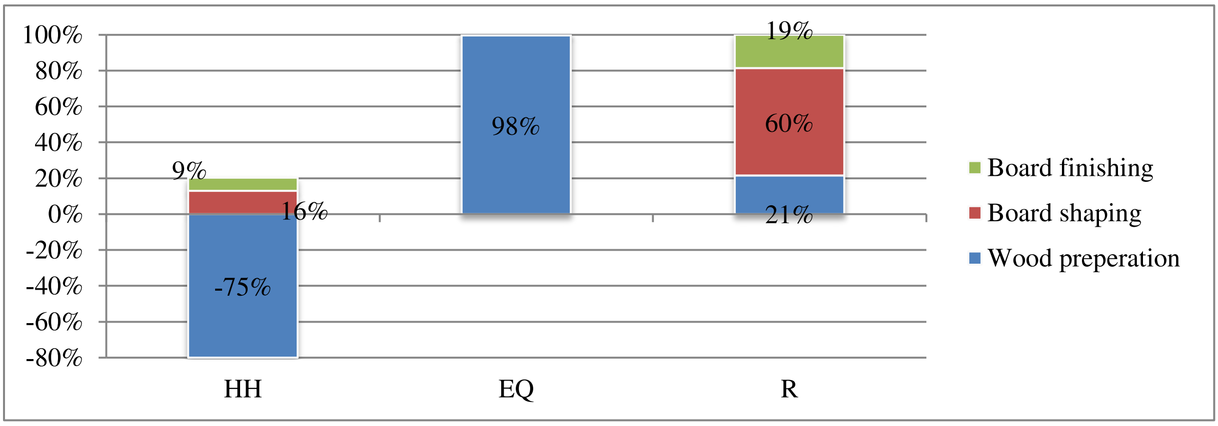

Figure 34: Impact assessment particleboard, SRC Characterization, EI99 (Own illustration.)

As illustrated in Figure 34, the wood preparation subsystem presents the highest negative contribution to HH and highest positive contribution to EQ. There are moderate values for board finishing and wood preparation subsystem and a high value for board shaping subsystem on R. Board finishing and – shaping have low influence on EQ (< 2%) and moderate influence on HH. These results are related to the same reasons described for conventional forestry.

Comparison of particleboards from conventional forestry and SRC

Figure 35 shows the comparison for the particleboard production. Particleboards from SRC have a higher negative value for HH and a smaller positive value for R as a result of the abandonment of paraffin wax during the board shaping subsystem and the different interior layer. However, due to the larger proportion of land use associated with wood production of SRC, EQ is much higher for SRC than for particleboards from conventional forestry. For normalization, particleboards from SRC have a high impact on EQ, a moderate impact on HH and a low one on R. Particleboards from conventional forestry have little to moderate impacts on HH, EQ and R.

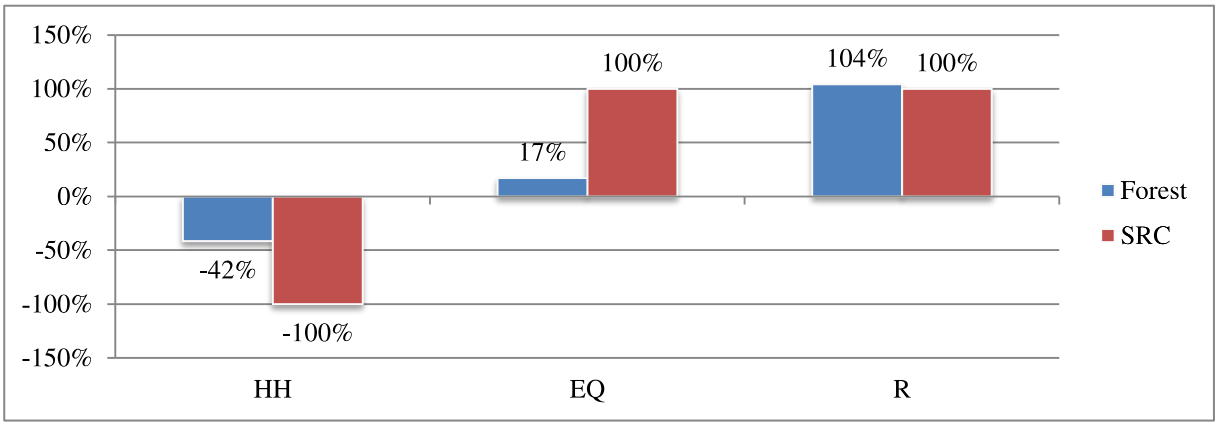

Figure 35: Comparative impact assessment particleboard, Characterization, EI99 (Own illustration.)

4.3.3 Summary of Results

Regarding the assumptions for LCI data (chapter 4.1.7) and uncertainties for different aspects of the LCA process itself as described in chapter 2.1 and 2.2 (e.g. uncertainties for Ecoindicator 99 and normalization procedure etc.), results have to be interpreted critical. Despite of the problematic issues of the results, which are further discussed in chapter 5, summarized outcomes of the present LCA are exposed below.

CML 2001

Production of woodchips

Except for GWP, where negative values of woodchips from forestry and SRC are almost equal but higher for SRC, woodchips from conventional forestry have lower positive values for EP, POCP and AP. Thus, according to the CML method and almost equal values for GWP, woodchips from conventional forestry are more environmental friendly. However, absolute values of normalization for both types of woodchips show that they have a great impact on GWP and minimal influence on EP, POCP and AP.

Combustion of woodchips

The combustion process itself is the largest contributor to all impact categories. Normalization shows that due to CO_2 emissions, the combustion of woodchips has a high impact on GWP There are low to moderate impacts on EP, POCP and AP.

Manufacturing particleboard

Due to input materials for the internal layer and paraffin wax for particleboards from conventional forestry, the production of particleboards with an interior layer from SRC is more environmental friendly according to the chosen CML categories. Normalization indicates, that the particleboard production has a large impact on ADP f. and GWP.

Ecoindicator 99

Production of woodchips

The assessment with Ecoindicator shows, that woodchips from SRC have higher positive values for EQ and R. It can be seen, that for normalized absolute values, both have a high impact on HH and a low on R. Woodchips from SRC have a large influence to EQ, whereas woodchips from forestry have a low one. Due to an almost equal impact on HH for both types of wood, the production of woodchips from conventional forestry can be seen as more environmental friendly according to Ecoindicator.

Combustion of woodchips

The combustion itself is the largest contributor on HH and EQ. The usage of electricity for machines during the combustion process is the largest contributor on R. Normalization shows, that it has great impact on HH through CO_2 emissions and small to moderate effects on EQ and R.

Manufacturing particleboard

Because of the interior layer and paraffin, the particleboard from conventional forestry has a higher value for R and a lower negative value for HH. Due to the land use, the particleboard from SRC has a higher impact on EQ. Thus, choosing EQ for a comparison, the particleboard from forestry has less environmental burdens. Taking HH or R for a comparison, SRC is a better choice from an environmental point of view. With normalization particleboards from SRC have a large influence on EQ and a moderate to HH. Both types have small to moderate influence on R. Particleboards from conventional wood have a small to moderate influence on HH and EQ.

Interior layer conventional Wood

It is striking, that for the direct comparison of the two types of woodchips, wood from conventional forestry is more sensitive from an environmental point of view. However, using wood from conventional forestry for the interior layer of the particleboard, wood from SRC appears to be more environmental reasonable according to the impact categories of CML and the Ecoindicator (except for EQ). Because, paraffin wax for particleboards from conventional wood has just a small influence on the results; the interior layer has to be examined. Energy and transport of the interior layer have the same quantities for both types of wood. Thus, the different types of conventional wood must be responsible for higher values of impact categories. Examining the interior layer, illustrated in Appendix XII, depicts that round wood has a high impact on the impact categories of CML and Ecoindicator. Especially the diesel consumption for round wood production is a great contributor to the impact categories of CML and Ecoindicator. Nevertheless, the round wood production is also responsible for the high negative values of GWP (CML) and HH (Ecoindicator). Despite of the negative values through the CO_2 storage, the diesel consumption for round wood production is the cause of the higher values of CML and Ecoindicator for particleboards from conventional wood.

4.3.4 Sensitivity Analysis

The sensitivity analysis is used in the present study because, it is recommended for comparative LCAs and additionally has versatility possibilities to address different types of uncertainty, which was shown in chapter 2. For the sensitivity analysis three scenarios are chosen. First, all scenarios are described. Subsequently changes of CML and Ecoindicator are illustrated and interpreted. The scenarios computed above, are adopted as the baseline scenario. Further information is attached in Appendix XIII.

Scenario 1: Reduction of diesel for the production of woodchips

As shown above, the diesel consumption for the production of woodchips was a great contributor to EP, POCP, AP (CML) and to R (Ecoindicator), respectively. For this reason, it shall be evaluated if a reduction of 10% of diesel has an impact to the respective impact categories. For conventional woodchips, that means a diesel consumption of 1,26*E-3 MJ instead of 1,4*E-3 MJ; for woodchips from SRC there is a value of 4,23*E-3 MJ instead of 4,7*E-3 MJ for the production of woodchips to produce 1 MJ of thermal energy.

As it is illustrated in Figure 36 and 37 the reduction of diesel has a considerable influence to EP, POCP and AP for both types of wood. There is a reduction of 9% to 10% of the respective impact category. The diesel consumption represents a hot spot for the production of woodchips. Except for GWP, which is mainly influenced by the CO_2 storage of wood, the consumption of diesel heavily affects the other impact categories. Nevertheless, it has to be considered, that for normalized values, the production of woodchips mainly influences GWP and not EP, POCP and AP.

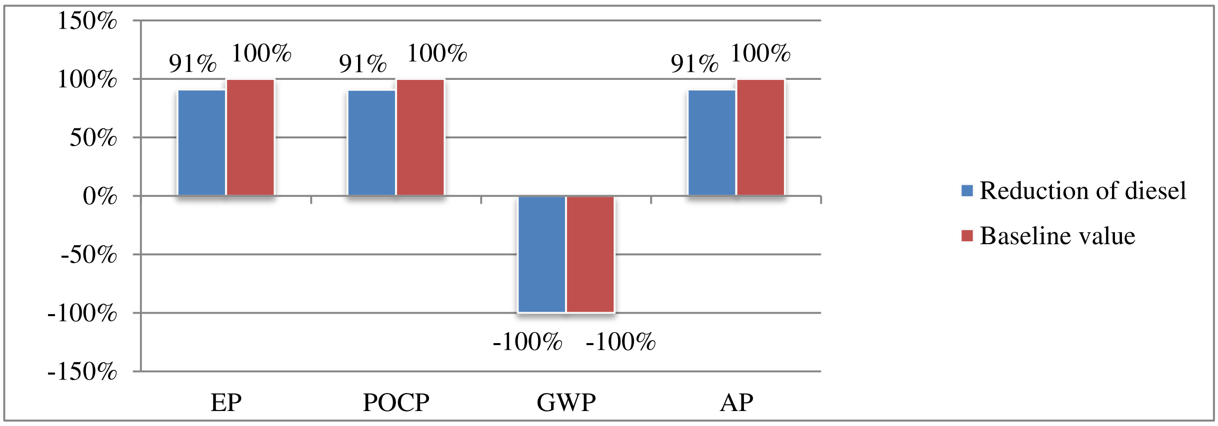

Figure 36: Reduction of diesel, conventional wood, CML
(Own illustration.)

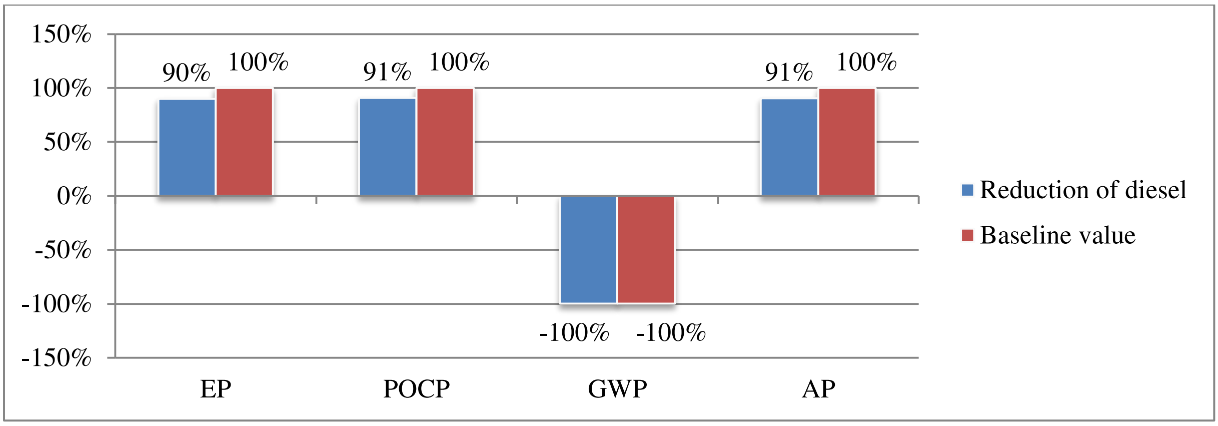

Figure 37: Reduction of diesel, SRC, CML
(Own illustration.)

As shown in chapter 4.3, the diesel consumption was a great contributor to R but not to HH and EQ for both woodchips types. Thus, the evaluation with the Ecoindictor shows that a reduction of diesel causes a reduction of R of 6% for conventional wood and of 7% for SRC; illustrated in Figure 38, 39. Thus, diesel consumption can be seen as a hot spot for R. However, HH and EQ are not affected, as they mostly depend on CO_2 and land use, respectively.

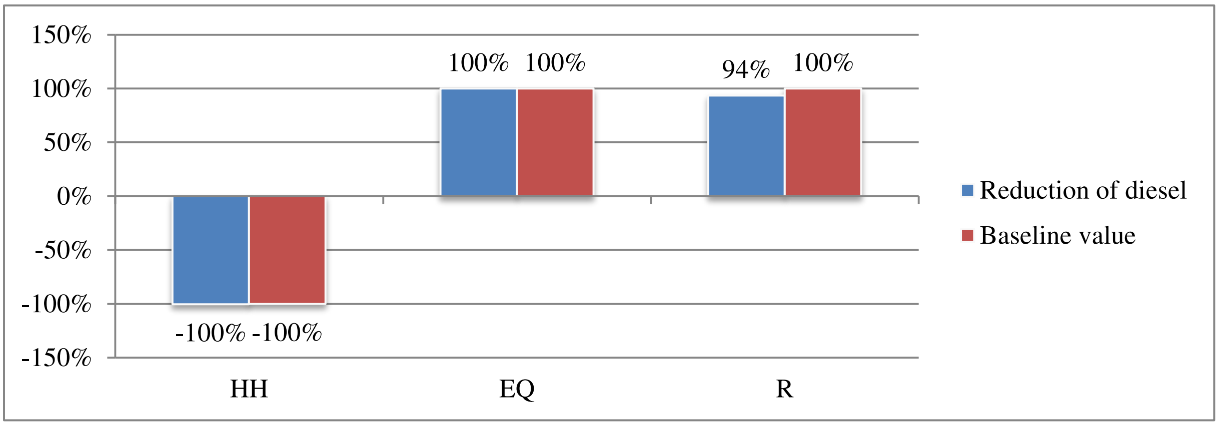

Figure 38: Reduction of diesel, conventional wood, EI99
(Own illustration.)

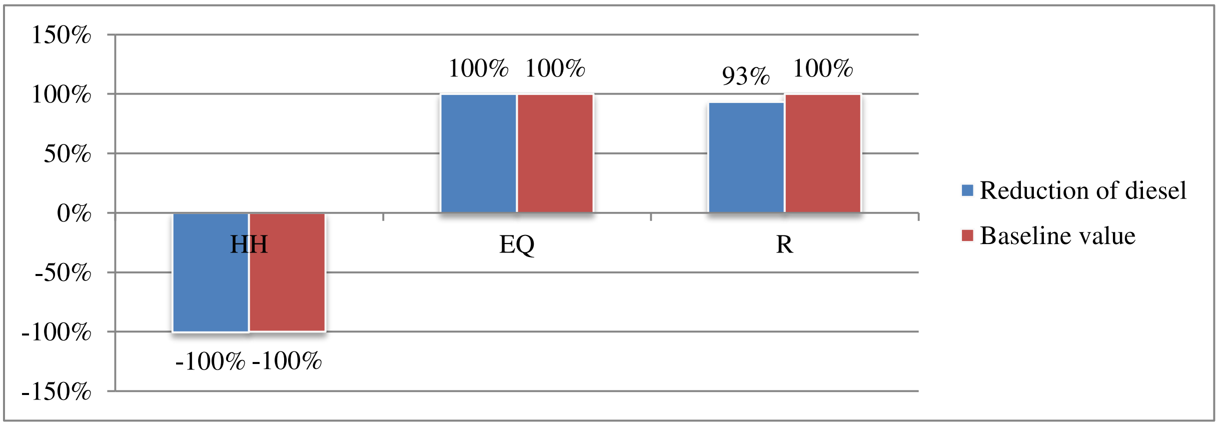

Figure 39: Reduction of diesel, SRC, EI99
(Own illustration.)

Scenario 2: Increasing the transport distance

As shown in the state of the art, GOGLIO, P.; OWENDE, P. (2009), evaluated the production, transportation and energy conversion of wooden biomass. They showed that the chip transportation distance is a major cause of variations of net energy production and total CO_2 emissions. Thereby, transportation distance smaller than 38 km significantly reduces the energy consumption and CO_2 emissions.[146] Based on this study it shall be evaluated how an increasing transport distance influences the results of CML and Ecoindicator. For the present study, a transport distance of 30 km from wood production place to firing station was assumed.

However, for larger firing systems transport distances can increase up to 50 km.[147] Thus, with the help of the sensitivity analysis an increasing distance from 30 to 50 km from wood production to firing system is evaluated. There is an increase of 3,3*E-3 tkm to 5,5*E-3 tkm.

Transport: 0,11 kg * 50 km = 5,5*E-3 tkm [weight of woodchips * new distance]

Despite the transport was not a great contributor to the categories of CML and Ecoindicator, results of CML, Figure 40 depict, that there is a marked rise of GWP (10%) which is mainly dependent on CO_2 emissions. There is a moderate increase of EP, POCP and AP. Thus, results of CML approve the outcomes from GOGLIO, P.; OWENDE, P. (2009), regarding a variation of CO_2 emissions through different transport distances. Nevertheless, there is a different picture for the evaluation with the Ecoindicator. As illustrated in Figure 41, an increasing transport distance has little to no effect to HH, EQ and R. The largest impact can be determined for HH; as it is partially dependent on CO_2 emissions through considering climate change.

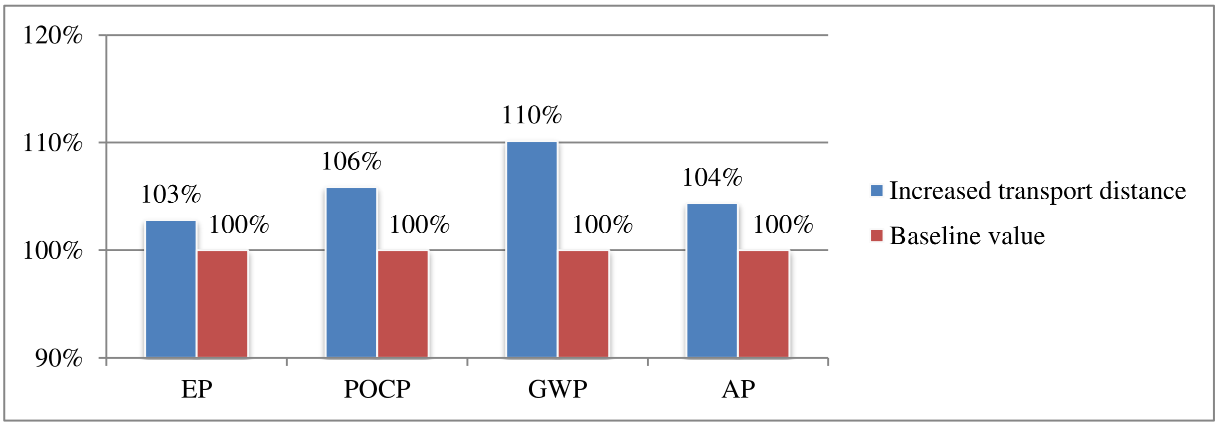

Figure 40: Increased transport distance, CML

(Own illustration.)

[146] Cf. GOGLIO, P.; OWENDE, P. (2009), p. 390 et seq.

[147] Cf. BAUER, C. (2007), p. 32.

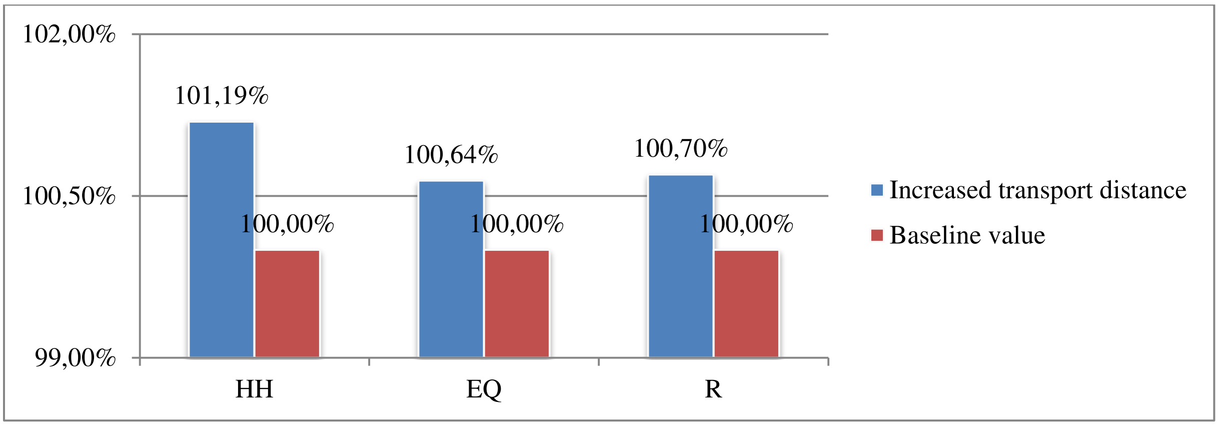

Figure 41: Increased transport distance, EI99
(Own illustration.)

Scenario 3: Substituting natural gas with thermal energy from a firing system for the production of particleboards

The energy consumption of the particleboard production is a major contributor to the impact categories. It shall be evaluated if energy from a renewable resource (wood) can improve the particleboard production from an environmental perspective. Thus, the third scenario examines the influence on CML and Ecoindicator if, instead of natural gas, thermal energy for drying processes of the wood preparation system is obtained from the wood firing system evaluated above.

In contrast to the present study which solely evaluated the particleboard production with energy from natural gas, the study of RIVELA, B. et al. (2005) also considered energy from combustion processes of wood for the drying processes at the preparation subsystem. Because, the study of RIVELA, B. et al. (2005) is the assessment basis of particleboard production in the present study, values of wood combustion processes of RIVELA, B. et al. (2005) are inherited for the sensitivity analysis: For the drier of the exterior layer there is a reduction of natural gas from 1037,20 MJ to 276,24 MJ and the usage of 760,96 MJ of thermal energy from the firing system. For the drier of the interior layer there is a reduction of natural gas from 2074,41 MJ to 560,86 MJ and the usage of 1513,56 MJ of thermal energy from the firing system.[148]

[148] Cf. RIVELA, B. et al. (2005), p. 108 et seq.

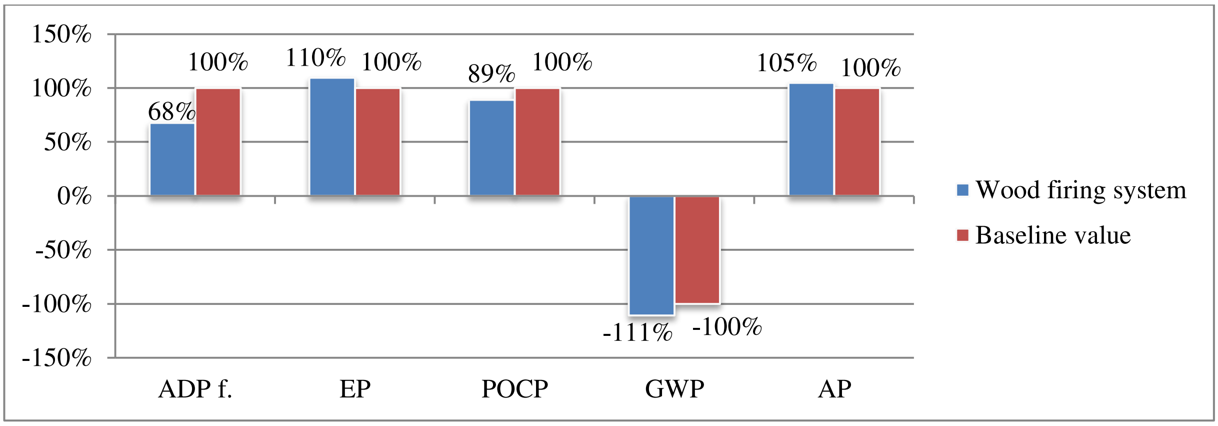

Figure 42: Production particleboard, conventional wood, substituting natural gas with wood firing system, CML (Own illustration.)

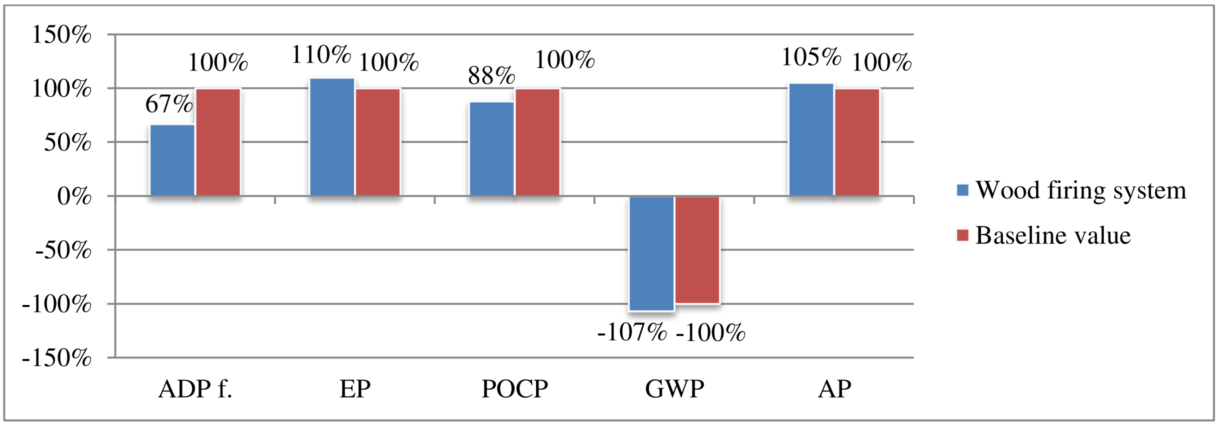

Figure 43: Production particleboard, SRC, substituting natural gas with wood firing system, CML (Own illustration.)

Results of CML for both types of wood in Figure 42, 43 show that, the use of energy from wood combustion processes instead of gas for particleboard production , lowers the values of ADP f. and POCP. It increases the values of EP and AP. Because less fossil energy (gas) is used; the value of ADP f. is decreasing substantially. Usage of wood for the firing system also increases the negative value of GWP. From an environmental point of view these are beneficial effects; as well as the reduction of POCP. However, because the combustion process highly contributes to EP and AP as shown above; there are increasing values for EP and AP.

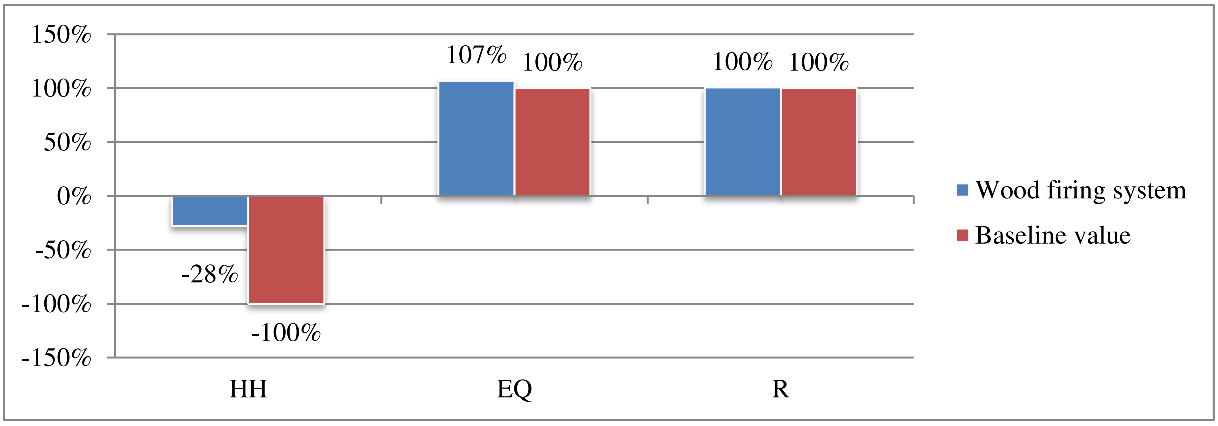

Figure 44: Production particleboard, conventional wood, substituting natural gas with wood firing system, EI99 (Own illustration.)

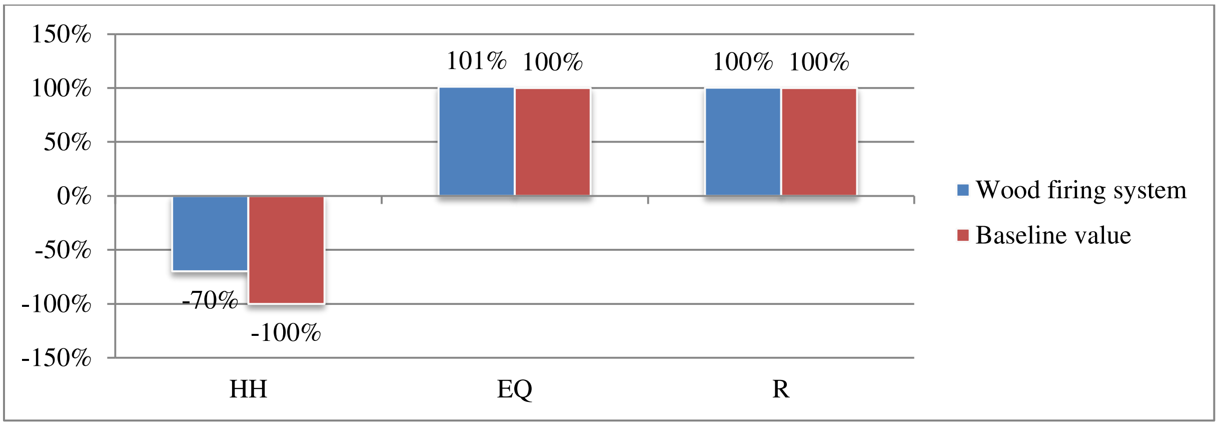

Figure 45: Production particleboard, SRC, substituting natural gas with wood firing system, EI99 (Own illustration.)

Figure 44 and 45 illustrate results of the Ecoindicator for both types of woodchips. No advantages using the wood firing system can be identified. There is an equal value for R and even a higher value for EQ based on the usage and modification of land for wood production processes as well as higher values for eutrophication and acidification through combustion processes. Due to high value for respiratory ailments, the combustion process is a great contributor HH. Thus, there is a lower negative value for the wood firing system in comparison with the baseline scenario.

5 Discussion

Aim of the present study was a comparative LCA between wood from SRC and wood from conventional forestry in order to investigate, if wood from SRC is a potential approach to solve problems regarding an increasing demand of wood for material and energetic purposes. Especially ecological issues were considered through the implementation of an LCA study.

There are advantages and disadvantages using LCA for an ecological comparison of wood. LCA is a very versatile instrument offering the possibility to evaluate different environmental influences of products regarding their whole life cycle. However, as shown above, there are great uncertainties for normalization, LCI and even LCIA which can have an influence on the results of LCA. Hence, LCA studies always have to be interpreted critically. Furthermore, LCA is a model, focusing on environmental issues that are important for the respective time or generation. Thus, they constantly have to be adapted to assess new social or ecological problems and new research findings. Because of this fact, the question arises, if science will ever be able to understand the whole impact of human action to environment, to develop a holistic LCA approach solving this problem. Nevertheless, LCA is an attempt dealing with the problematic issue to evaluate the impact of human acting on the environment.

Moreover, it could be shown, that despite of an ISO standardization process, especially LCAs of wood are hardly to compare. Depending on scope, LCIA method, estimations and assumptions results of the LCA can differ. Hence, further standardization processes are useful; under considering whether they restrict or support LCA regarding a meaningful data basis and comparability.

Using software for LCA simplifies the compiling of LCI and LCIA substantially. Databases like “Ecoinvent” as well as a good handling of combining and calculating data of LCI, LCIA, uncertainties, etc. through software, supports the implementation of LCA of further products. From an environmental point of view this is beneficial as LCA studies help to understand environmental influences. However, the critical point about using software is the probably limited understanding of the calculations “behind” the results provided by the software. Most software solutions supply the usage of midpoint and endpoint approaches for the evaluation of LCIA.[149] For the present study CML 2001 and Ecoindicator were used which lead to partially different results. Hence, to meet the goal of a study, the user has to know the functioning of the method and the kind of problem he wants do discuss. Only with that knowledge a targeted choice of mid- or endpoint approach is possible. However, as it is very complicated to understand the whole structure of a method, the author of the present study recommends the parallel usage of mid- and endpoint approaches to cover a broad range of environmental issues. Despite the lively discussion about end or midpoint modeling shown in chapter 2.1, assessing “land use” is an appreciable difference between CML and Ecoindicator. As the Ecoindicator assesses land use and -modification, the CML method does not. Although both methods are not comparable, this difference leads to various assertions regarding the assessment of wood. On the evidence of the continuous sealing of natural grounds for new agriculturally or settlement areas it is necessary to consider land use as a pollutive factor. Results of the Ecoindica-

[149] WIMMER, R.; BERTSCH, T. (1997), p. 21 et seq.

tor consider land use and modification as a parameter of “EQ”, but further influencing variables concerning the kind of land is used (e.g. desert or tropical forest), how is the land used (Cultivation of forestry or a coal power station), the existing quantity of the used land and physical interventions (fragmentations of landscape or the distortion of soil), are not applicable. These influencing variables should be assessed differentially as they have various impacts to the environment. Especially for the present study it is questionable to assess wood production as a great impact factor on EQ.

As described above, EQ expresses the potentially disappeared fraction of species due to an environmental impact. Although forest for industrial purposes does not conform to its natural state; it is still an ecosystem fulfilling important tasks for human being and nature. Furthermore, the cultivated forest is a habitat for diverse species.[150] Thus, it is questionable in what way these positive characteristics are assessed and if there is a different assessment if the land is used for probably more harmful purposes (e.g. coal power station). However, land usage for the cultivation of SRC has to be seen different from conventional forestry, as SRCs are used more intensively. Thus, it should be considered how an application of pesticide or fertilizer and a repeated harvesting within a short period of time influences the qualities of the used land. Whether and how these issues are respected concerning the assessment of land use and EQ respectively, is not applicable.

A full understanding of the assessment of the Ecoindicator and endpoint modeling, respectively is quite complicated. Hence, the user might not understand the assessment structure of the Ecoindicator, which is a substantial disadvantage of endpoint modeling. On one hand endpoint modeling helps to better understand the results of a study, on the other hand, assessment methods are difficult to comprehend. Finally, it is questionable, how far all relevant environmental influences are treated with CML and Ecoindicator. After all, it is a fact, that impacts on the environment can only be assessed if they are known. Thus, results of Ecoindicator and CML are just as good as sciences understand the coherence between human acting and environment.

Aim of the study was to answer three research questions:

Question *q1:* Regarding the energetic usage of wood, the present study reveals, that using woodchips from conventional forestry is more reasonable from an environmental point of view. However, apart from uncertainty, normalized values show that the production of both types of woodchips is climate friendly due to its substantial CO_2 storage. The examination of combustion showed, that the combustion process itself is a great contributor to all categories of CML and to the most of Ecoindicator. Moreover, the sensitivity analysis of the present study indicated that modifying the diesel consumption for the production of woodchips, the transport distance as well as the combustion of wood for production of particleboard has moderate to strong effects on CML and Ecoindicator.

Comparing the production of woodchips from conventional forestry with the state of the art; results of the present study get partly confirmed. The assessments of ZIMMER, B. (2010) and

[150] Cf. BAYRISCHES STAATSMINISTERIUM FUER ERNAEHRUNG; LANDWIRTSCHAFT UND FORSTEN, (eds.) (2010), w. p.

ELTROP, L. et al. (2006) show, in line with results for CML of the present study, that the usage of fossil fuels (diesel) is dominating in the production phase which is most environmental unfriendly.[151] Furthermore, results of ZIMMER, B.; WEGENER, G. (1996) that the intensity of the technical production has a crucial effect to the LCA of wood can be confirmed too.[152] Nevertheless, at this point, differences between Ecoindicator and CML become obvious. Beside fossil fuels, also gravel and land use are great contributors to the impact categories of the Ecoindicator. Like mentioned above, the user has to weigh between mid- or endpoint approach dependent on the required results. Despite to that, normalized values of the present study reveal that woodchips from forestry are environment- and climate friendly. However, as revealed by the sensitivity analysis, especially the diesel consumption is a hot spot. A reduction has a considerable influence to categories of CML and R (Ecoindicator). Regarding environment, a minimal consumption of all inputs and especially of diesel should be aspired.

Comparing results of the production of woodchips from SRC with the state of the art, studies of ROEDL, A. (2008), BURGER, F. (2010) confirm that there is negative global warming potential for the production phase. However, diesel consumption accounts for the largest part of the environmental burdens if there is no fertilization.[153] Whereas some studies renounce fertilization[154], studies of ROEDL, A. (2008), HELLER, M.; KEOLEIAN, G.; VOLK, T. (2002) depict that using fertilizer causes great differences on results of impact categories.[155] Using the environment friendly option, the present study also renounced fertilization. Nevertheless, it has to be considered, that fertilizer would increase the environmental burdens of woodchips from SRC. Thus, for comparison with woodchips from forestry, woodchips from SRC would have even higher values for impact categories of CML and Ecoindicator. Moreover, BURGER, F. (2010) points out that cultivation of SRCs is an extensive land use. This outcome can be confirmed based on the results of the Ecoindicator. Beside diesel consumption and land use herbicides are determining according to the Ecoindicator. However, with normalization diesel and herbicides have little to no effects. Thus, based on a critical review of normalization and except for the land use, the production of woodchips from SRC is environment- and climate friendly. Nevertheless, regarding environment, a minimal consumption of all inputs should be aspired. Like for conventional wood, especially the consumption of diesel and the land usage as hot spots, should be reduced.

Watching the combustion of woodchips, the present study reveals that depending on the respective LCIA approach, transport, electricity and the combustion itself have a great influence on the outcomes of the LCA. As illustrated in the sensitivity analysis, an increasing quantity of tkm has considerable influences on the result especially for GWP (CML). ROEDL, A. (2008) and GOGLIO, P.; OWENDE, P. (2009) confirm these outcomes. Whereby ROEDL, A. (2008) considered the weight of the transported biomass, GOGLIO, P.; OWENDE, P. (2009) assessed the transport distance.[156] Both issues are important as the transport is measured in tkm (t * km). Hence, the characteristics of wood should be considered: As the weight of wood

[151] Cf. ZIMMER, B. (2010), p. 22 et seq.; Cf. ELTROP, L. et al. (2006), p. 49 et seq.
[152] Cf. ZIMMER, B.; WEGENER, G. (1996), p. 217 et seq.
[153] Cf. ROEDL, A. (2008), p. 14 et seq.; Cf. BURGER, F. (2010), p. 83 et seq.
[154] Cf. BURGER, F. (2010), p. 83 et seq.
[155] Cf. ROEDL, A. (2008), p. 14 et seq; Cf. HELLER, M.; KEOLEIAN, G.; VOLK, T. (2003), p. 160 et seq.
[156] Cf. ROEDL, A. (2010), p. 573 et seq.; Cf. GOGLIO, P.; OWENDE, P. (2009), p. 390 et seq.

is dependent on the water content, wood should be transported after a drying process. Moreover, the idea of railway siding as an environmentally friendly type of transportation seems reasonable.[157] Like ELTROP, L. et al. (2006)[158], the author of the present study also recommends an optimal adaptation to local circumstances for a minimum of environmental burdens. However, using the Ecoindicator, transports as well as increasing transport distances have a minor role. Hence, focalizing on the results of the Ecoindicator, an environmentally friendly adaptation of the transport conditions would not necessarily be required. Furthermore, RAFASCHIERI, A.; RAPACCINI, M; MANFRIDA, G. (1999) recommend the usage of biodiesel to reduce CO_2 emissions.[159] This is critical, as diesel from biomass may lower CO_2 emissions, but increases the land use and with that EQ (Ecoindicator) as even more cultivation areas for biomass are necessary. Comparing, outcomes of the present study with ELTROP, L. et al. (2006), both studies show, that most environmental damages are arising from the releasing emissions during the combustion process of wood. Furthermore, the sensitivity analysis of the present study depicts that, substituting gas with energy from a wood firing system, increases the values of AP and EP (CML). Additionally, observing the outcomes of the Ecoindicator, from an environmental point of view, the particleboard production with a wood firing system cannot be recommended. However, results of ELTROP, L. et al. (2006), that CO_2 emission are much lower if wooden products are used for energy production instead of fossil fuels, can be approved using CML. The authors further advocate for an expansion of using wood as an energy source.[160] This opinion has to be seen critically. It can only partly been endorsed because results of the sensitivity analysis show that benefits of using wood as an environmentally friendly option for energetic purposes are limited. Moreover, outcomes of the sensitivity analysis for wood combustion depended on the respective mid- or endpoint approach and even single impact categories. Lowering the environmental burdens of the combustion process, ELTROP, L. et al. (2006) recommend the usage of filters or purification cleaners.[161] This possibly helps; but it should be minded, that production, usage and disposal of this techniques cause not even more environmental burdens than the combustion without it. Despite the environmental burdens through the combustion of wood, the undeniable benefit of this energy source is the fact that wood is renewable. Like mentioned from RICHTER, K; GUGERLI, H. (1996), wood products usually come from a raw material which is a component of an ecosystem itself.[162] Furthermore, with a sustainable forestry the combustion of wood is almost CO_2 neutral and with that, at least climate friendly.

Moreover, results of the present study and BURGER, F. (2010) reveal that electricity plays a major role as there is a high consumption of the firing system.[163] As in the present study an electricity mix of fossil and renewable energies resulted in high values for R (Ecoindicator) and EP (CML), solitary electricity consumption from renewable energies possibly decrease the environmental burdens. Nevertheless, regarding the problematic issues "land use" and

[157] Cf. ZIMMER, B. (2010), p. 22 et seq.
[158] Cf. ELTROP, L. et al. (2006), p. 49 et seq.
[159] Cf. RAFASCHIERI, A.; RAPACCINI, M; MANFRIDA, G. (1999), p. 1491.
[160] Cf. ELTROP, L. et al. (2006), p. 49 et seq.
[161] Cf. ELTROP, L. et al. (2006), p. 49 et seq.
[162] Cf. RICHTER, K; GUGERLI, H. (1996), p. 225 et seq.
[163] Cf. BURGER, F. (2010), p. 83 et seq.

"wood combustion", it has to be noted, that at least using renewable energy from wood has to be seen critical.

Additionally, ZIMMER, B. (2010) calculates with a substitution effect for the combustion of wood. This effect is only reasonable if wood is coming from sustainable forestry. Furthermore, it is just computable if there is a comparable energy production through fossil energy. For a better comparability with other studies, this effect has not been calculated in the present study. Furthermore, the influence of diverse storage methods on woodchips and the efficiency of the power plant mentioned by ZIMMER, B. (2010) could not be assessed, as the present study uses data from the state of the art and the ecoinvent database.[164] However, implementing an on-site measurement these aspects could be assessed more elaborately.

q2: Due to different outcomes of Ecoindicator and CML, the second research question cannot be answered unequivocally. Depending on the assessment approach and impact categories both type of woodchips are more or less reasonable, regarding the material usage from an environmental perpective. Again, the differences between Ecoindicator and CML become clear: Using CML, particleboards from SRC have less environmental burdens. Using the Ecoindicator and assuming that EQ as well as land use and modification, respectively, are highly environmentally relevant, particleboards from SRC would not be advisable. However, despite the high energy consumption and the extensive land modification for SRC, normalization reveals, that the particleboard production is climate-friendly due to the CO_2 storage.

Comparing the results of the present study with the state of the art, outcomes of the study of WEGENER, G.; FRÜHWALD, A.; SCHARAI-RAD, M. (1997) can be confirmed partially. Like in their study, the intern utilization of waste wood was also taken into account in the present study. As a result, the authors showed that during the particleboard production emissions in the air have higher amounts than emissions for water and soil.[165] This result leads to the problem, that the quantity but not the impact of the emissions is visible. Hence, this kind of assessment was not evaluated in the present study as it is questionable if an interpretation of this result is feasible. The present study concentrates on the evaluation of the impact categories of CML and Ecoindicator, irrespective of the quantity of emissions for water, air and soil.

Outcomes of the present study and the study of RIVELA, B. et al. (2005) have to be compared considering that the study of RIVELA, B. et al. (2005) was used as a baseline survey. Due to modifications the comparison has to be seen critically. In the present study board shaping- and wood preparation- and not the board finishing subsystem, have the greatest impact on the impact categories for both types of woodchips. Furthermore, for the present study the wood preparation- and not the board shaping had a great contribution to the damage to ecosystem quality. However, the high impact of gas to the Ozone layer category, which is a component of HH can be affirmed.[166] Nevertheless, for the present study, the wood preparation subsystem was the greatest contributor to HH. These different outcomes result from the modifications of the LCA of RIVELA, B. et al. (2005) in the present LCI.

[164] Cf. ZIMMER, B. (2010), p. 22 et seq.
[165] Cf. WEGENER, G.; FRUEHWALD, A.; SCHARAI-RAD, M. (1997), p. 16 et seq.
[166] Cf. RIVELA, B. et al. (2005), p. 112 et seq.

However, RIVELA, B. et al. (2005) encouraged the reuse and recycling of wood with a final energy recovery.[167] Considering the strong impact of wood on land use and the possibility of an advantageous CO_2 storage as shown in the present study, an efficient use of wood through recycling is reasonable. Moreover, the advantages of a cascade utilization of wood described in chapter 3.2.1 supports these statements.

Results of the study of FRÜHWALD, A.; RAD-SCHARAI, M.; HASCH, J, (2000) revealed that the energy demand of the particleboard production is a crucial factor for acidification and eutrophication. However, they additionally showed that partilceboards have an advantageous CO_2 balance if wood comes from sustainable forestry.[168] These outcomes are in accordance with the results of the present study which further show, that the energy demand is also a crucial factor for POCP and ADP f. for both woodchips. The authors further figured out that glue and binder considerably contribute to acidification, which has to be confirmed. Whereby the present study reveals, that it further considerably contributes to POCP and ADP f.. Like for the results of the sensitivity analysis of the present study, the authors evaluated that especially the combustion of wood for the energy supply of the particleboard is unfavorable. They therefore recommended “end of pipe” technologies like particle filters to reduce unwanted emissions, too.[169] As mentioned above, “end of pipe” technologies have to be seen critical. Further LCA studies have to assess their environmental burdens to ensure that their usage is reasonable from an environmental point of view. As the combustion of waste wood is unfavorable, it should be used for material processes of the wood preparation subsystem. That leads to the problem that other energy sources for the particleboard production are necessary.

Moreover, evaluating the interior layer reveals that the round wood production leads to the larger environmental burdens for the particleboards from conventional forestry. Except for EQ (Ecoindicator) particleboard from conventional forestry are less advisable from an environmental perspective. However, with respect to combustion, conventional woodchips were produced from wood residues leading to the result that these woodchips have less environmental burdens than chips from SRC. Thus, a general conclusion if conventional wood or SRC should be used is not possible. The evaluation between conventional wood and SRC depends, apart from the assessing method, also on the selected components of the trees from conventional forestry. Due to wood residues from conventional forest are byproducts, this circumstance leads to the issue of allocation in LCA. As described in chapter 4.1.6, different allocation procedures can have a significant influence on the result of LCA.[170] For the present LCA data and allocation procedures were adopted from Ecoinvent. However, using other databases or allocation procedures, results can be different. Hence, comparing woodchips from conventional forestry and SRC, the evaluation is also dependent on the components transformed to woodchips and allocation procedures. However, for woodchips from SRC this problem does not matter as the whole tree is usually processed to woodchips. Based on the results of the present LCA and from an ecological point of view, the use of woodchips from wood residues for the particleboard production would be recommendable. Nevertheless, it is questionable if

[167] Cf. RIVELA, B. et al. (2005), p. 112 et seq.
[168] Cf. FRUEHWALD, A.; RAD-SCHARAI, M.; HASCH, J, (2000), p. 114 et seq.
[169] Cf. FRUEHWALD, A.; RAD-SCHARAI, M.; HASCH, J, (2000), p. 114 et seq.
[170] Cf. JUNGMEIER, G. et al. (2002), p. 290 et seq.

woodchips from wood residues meet the quality requirements of the particleboard. Furthermore, it has to be assessed if the quantity of wood residues can cover the demand of wood for the particleboard industry.

Furthermore the cascaded utilization has to be discussed. As described in chapter 3.2.1, due to the efficiency use of resources, a cascaded utilization of wood is recommendable. Outcomes of the present study showed that a material usage of SRC for producing a particleboard is reasonable from an environmental point o view. Using wood from SRC for material products is the first step towards recycling and with that towards cascaded utilization. However, it still has to be considered, that the production of particleboards from SRC was implemented experimentally.[171] Thus, it is questionable if a large-scale production of particleboards from SRC leads to the same outcomes of LCA and the same quality of the particleboards. Moreover, considering the quality loss per application mentioned by SIRKIN, T.; HOUTEN, M. (1994)[172], for both particleboard types, further research is necessary to evaluate how far cascading processes can be implemented and if they are environmentally friendly too. As it is shown in the state of the art, the final combustion of a wooden product is the last phase of cascaded utilization.[173] However, because of processing glues and binders for the particleboard it is critical if combustion of wooden products including these ingredients is still useful regarding the environmental burdens.

Finally, it has to be considered that despite potential ecological advantages a cascaded utilization is only possible, if product characteristics, production conditions, economic and social requirements as well as customer needs enable recycled products.[174]

q3: Question three was partly answered above. It needs to be emphasized, that there is no “ecological winner” in general. Depending on assessment method and energetic or material usage, conventional wood or wood from SRC is the better choice from an environmental point of view.

Furthermore all results of the present study have to be interpreted critically. Despite the general uncertainty for LCA the present study used and also modified data from literature as shown in the pedigree matrix. This leads to further uncertainty; but was necessary in order to implement a first attempt regarding a comparative assessment of the wood types without on site measurement.

Despite the evaluated ecological aspects of the wood production and also mentioned by RICHTER, K.; GUGERLI, H. (1996), forestry is more than a provider of raw material.[175] Further important tasks of the forest should not be ignored. Especially “social services” of the forest like climate regulation, filtering of air and water or the accommodation of species should be considered in further LCA studies. However, as it is very sophisticated to assess these tasks regarding their environmental impact, it would probably complicate the comparison of SRC and conventional wood. It is also questionable to what extent SRCs can fulfill

[171] Cf. WILCZYŃSKI, A. et al. (2011), p. 194.
[172] Cf. SIRKIN, T.; HOUTEN, M. (1994), p. 214 et seq.
[173] Cf. ARNOLD, K. et al. (2009), p. 18 et seq.
[174] Cf. ARNOLD, K. et al. (2009) p. 27 et seq.
[175] Cf. RICHTER, K.; GUGERLI, H. (1996), p. 225 et seq.

these “ecological tasks” too. Despite social and economic aspects of forest and SRC play a minor role for an ecological assessment; to gain an overall picture, they should be taken into account as well.

6 Conclusion

Implementing an ecological assessment with LCA, uncertainties have to been taken into account. Thus, a critical review of LCA studies is necessary. For the LCIA the usage of mid- and endpoint is recommendable. If just one approach shall be used, advantages and disadvantages of the respective approach have to be considered. Due to different characteristics of assessment methods the user has to choose a method depending on the aim of the study. Using LCA software helps to implement the study but decreases the understanding of the assessment method.

For the production of woodchips from SRC and conventional wood, an optimal adaptation to local circumstances is reasonable to decrease the diesel consumption as the main contributor to the impact categories of CML and to R (Ecoindicator). The production of woodchips from conventional forestry causes very little environmental burdens. It is further climate friendly due to the great CO_2 uptake. Compared to woodchips from conventional wood, the production of woodchips from SRC is less environmental friendly. However, despite the extensive land use, woodchips from SRC have just little environmental burdens too. Like conventional wood they are climate friendly due to CO_2 uptake. Fertilization should be avoided as the state of the art shows that environmental burdens would be even higher for woodchips from SRC. Nevertheless clarifying studies concerning advantages, disadvantages and environmental aspects of fertilization would be desirable.

Due to ecologically harmful emissions releasing during the combustion process, the combustion of wood has to be seen critically. Sustainable forestry decreases the environmental burdens associated to CO_2. End of pipe solutions like filters could reduce emissions responsible for high values of POCP, AP, EP and respiratory ailments (HH). However, further studies are necessary to evaluate the environmental compatibility of a combustion including end of pipe solutions. The present study showed that dependent on the assessment method, using wood for thermal energy is just partly recommendable compared to energy from gas. Further comparative studies are necessary to detect the renewable energy source with the lowest environmental burdens.

Despite the higher environmental burdens of particleboards from conventional wood for CML, the present study reveals, that processing wood from conventional forestry and SRC for particleboards is climate friendly through CO_2 storage. For particleboards from conventional wood, further studies need to assess if woodchips from wood residues can replace round wood as round wood leads to greater environmental burdens. Compared to particleboards from conventional wood, the particleboard from SRC causes less environmental burdens; except an extensive land use. Hence, regarding ecological aspects, the usage of wood from SRC for material utilization can be reasonable with an efficient land use. With a material usage of wood from SRC a cascaded utilization is possible. Furthermore, to decrease land use and efficiently deploy resources, the cascaded utilization has to be recommended. With cascaded utilization and the usage of byproducts, the particleboard production uses renewable resources in an ecologically reasonable way. However, further studies are necessary, to evaluate if and how a recycling of particleboards can be realized. The cascade with minimal environmental burdens has to be implemented. Due to the high energy consumption during the particleboard production, an environmentally friendly energy supply is necessary.

The present LCA study reveals that outcomes depend on the assessment method as well as wood components of conventional wood and allocation procedure, respectively. However, in order to improve the outcomes and decrease the uncertainty regarding the data quality, an on-site measurement should be implemented. Moreover, the present study evaluated the wood production. Other environmental issues regarding forestry should be examined more elaborately.

Nevertheless, the present study reveals that with an efficient land use, wood from SRC can improve the wood provision. Wood from SRC can help to cover the increasing demand of wood for material and energetic purposes in an environmental friendly way.

Appendix

Appendix I: Databases and Ministries

Table 10: Databases

Database	Short description	Uniform Resource Locator
EconBiz	German virtual library of economics.	http://www.econbiz.de/
CAB Abstracts	Database of bibliographic information for agriculture and adjacent fields.	http://www.cabi.org
Web of Science	Interdisciplinary database amongst others for economics and environmental management	http://portal.isiknowledge.com
Science Direct	Database for scientific, technical and medical full text research.	http://www.sciencedirect.com/
Databases under EBSCO	Scientific full text database system. Particularly considertaion of "Acedamic Source Complete" and "Business Source Complete".	http://search.ebscohost.com/
HOLZ	Database of bibliographic information for german and international literature especially about wood processing.	http://www.dbod.de/db/
Google Scholar	Provides a search of scholarly literature across many sources, including theses, books, abstracts and articles.	http://www.google.de/scholar
Emerald	Database of journals and books for business and management.	http://www.emeraldinsight.com/
WISO	German database system of economics and social science.	http://www.wiso-net.de/

(Own illustration.)

Table 11: Ministries and relevant articles

Ministries	Articles
BAYRISCHE LANDESANSTALT FÜR FORST UND LANDWIRTSCHAFT	Energieinhalt von Holz[176]
BAYRISCHES STAATSMINISTERIUM FÜR ERNÄHRUNG; LANDWIRTSCHAFT UND FORSTEN	Der Wald als Lebensraum und Ökosystem[177]
MINISTERIUM FÜR ERNÄHRUNG, LANDWIRTSCHAFT, FORSTEN UND FISCHEREI, MECKLENBURG VORPOMMERN	Schnellwachsende Baumarten auf landwirtschaftlichen Flächen[178]
BUNDESMINISTERIUM FÜR ERNÄHRUNG, LANDWIRTSCHAFT UND VERBRAUCHERSCHUTZ, BMELV	Waldstrategie 2020 Nachhaltige Waldbewirtschaftung[179] Zugunsten Von Klima, Lebensqualität, Innovationen Und Arbeitsplätzen[180]
BAYRISCHE LANDESANSTALT FÜR WALD UND FORSTWIRTSCHAFT	Das Holz der Weide[181]

(Own illustration.)

176 BAYRISCHE LANDESANSTALT FÜR FORST UND LANDWIRTSCHAFT (eds.) (2012), p. 1.
177 BAYRISCHES STAATSMINISTERIUM FÜR ERNÄHRUNG; LANDWIRTSCHAFT UND FORSTEN, (eds.) (2010), w. p.
178 ROEHRICHT, C.; RUSCHER, K. (2009), p 1.
179 BUNDESMINISTERIUM FÜR ERNÄHRUNG, LANDWIRTSCHAFT UND VERBRAUCHERSCHUTZ, BMELV (eds.) (2009), p 1.
180 BUNDESMINISTERIUM FÜR ERNÄHRUNG, LANDWIRTSCHAFT UND VERBRAUCHERSCHUTZ, BMELV (eds.) (2004), p. 1.
181 GROSSER, D. (2005), p. 1.

Appendix II: Search Strings and Results

Table 12: Search strings and results

Search strings and combinations	Google Scholar	EBSCO-host (ASC,BSC)	EconBiz	Emerald	Science Direct	WISO	Web of science	CAB Ab-stracts	HO-LZ
ökobilanz AND holz* OR forst* OR wald* OR kup OR kurzumtriebs-plantage	2060 (24)	-	1377 (1)	-	-	1008 (1)	-	-	141 (2)
lca OR life cycle assessment AND holz* OR forst* OR wald* OR kup OR kurzumtrieb-splantage	5190 (3)	-	1375 (3)	-	-	1280 (0)	-	-	18 (0)
kaskadennutzung AND LCA AND holz* OR forst* OR wald* OR kup OR kurzumtriebs-plantage	112 (1)	-	1377 (1)	-	-	1119 (0)	-	-	0 (0)
ökobilanz AND kaskadennutzung AND holz* OR forst* OR wald* OR kup OR kurz-umtriebsplantage	31 (0)	-	1237 (0)	-	-	1205 (0)	-	-	0
ecobalance AND wood OR timber OR lumber OR forestry OR forest OR woods OR short rotation for-estry OR short ro-tation plantation OR short rotation coppice	40 (1)	~4300 (4)	824 (2)	336	5 (0)	1261 (0)	0 (0)	524 (3)	1 (0)
lca OR life cycle assessment AND wood OR timber OR lumber OR forestry OR forest OR woods OR short rotation for-estry OR short ro-tation plantation OR short rotation coppice	4470 (3)	~4300 (3)	824 (0)	10 (2)	1594 (4)	964 (0)	143 (0)	554 (0)	0 (0)

Search strings and combinations	Google Scholar	EBSCO-host (ASC,BSC)	EconBiz	Emerald	Science Direct	WISO	Web of science	CAB Ab-stracts	HO-LZ
cascading OR cascaded utilization AND wood OR timber OR lumber OR forestry OR forest OR woods OR short rotation forestry OR short rotation plantation OR short rotation coppice	5 (0)	~4300 (2)	829 (0)	0 (0)	61 (0)	840 (0)	89 (0)	443 (0)	0 (0)
cascading OR cascaded utilization AND ecobalance OR lca OR life cycle assessment AND wood OR timber OR lumber OR forestry OR forest OR woods OR short rotation forestry OR short rotation plantation OR short rotation coppice	162 (0)	~4300 (0)	894 (0)	0 (0)	44 (1)	687 (0)	92 (0)	498 (0)	0 (0)

(Own illustration.)

Appendix III: Articles of LCA for Conventional Forestry

Table 13: Articles of LCA for conventional forestry

Author	**Year**	**Topic**	**Wood production**	**Transformation**	**Utilization**	**Recycle (material usage)**	**Disposal**
Material Usage							
RICHTER, K.; GUGERLI, H.[182]	1996	Comperative LCA of wood	X	X	X		
SCHWEINLE, J.[183]	1997	LCA production of raw wood	X	-	-	-	-
WEGENER, G.; ZIMMER, B.; FRUEHWALD, A. [184]	1997	LCA production of particleboards, windows, paper, laminated wood	X	X	-	-	-
SEPPÄLÄ, J.[185] et al.	1998	LCA of forest industry and environment of Finland	X	X	-	-	-
FRÜHWALD, A.; RAD-SCHARAI, M.; HASCH, J.[186]	2000	LCA of particleboards	X	X	X	X	X
NEBEL, B.; WEGENER, G.; ZIMMER, B.[187]	2002	LCA of wooden floors	X	X	X	-	X
WHITE, M. et al.[188]	2005	LCI of roundwood production	X	X	X	X	X
RIVELA, B. et al.[189]	2006	LCI of particleboard	X	X	X	X	X
ALBRECHT, S. et al.[190]	2008	LCA of wooden floors and walls	X	X	X	X	X
SCHEER, D.[191]	2008	LCA of wood houses and windows	X	X	-	-	-
GONZÁLEZ-GARCÍA, S. et al.[192]	2009	LCA of hardboard manufacture	X	X	-	-	-
TUCKER, S.; SYME, M.; FOLIENTE, G.[193]	2009	LCA of wooden products in Australia	X	X	-	-	-
GONZÁLEZ-GARCÍA, S. et al.[194]	2011	LCA of production of wood boxes	X	X	-	-	-

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182 RICHTER, K.; GUGERLI, H. (1996), p. 2 et seq.
183 SCHWEINLE, J. (1996), p. 6 et seq.
184 WEGENER, G.; FRÜHWALD, A.; SCHARAI-RAD, M. (1997), p. 37 et seq.
185 SEPPAELAE, J. et al. (1998), p. 87 et seq.
186 FRÜHWALD, A.; RAD-SCHARAI, M.; HASCH, J. (2000), p. 23 et seq.
187 NEBEL, B.; ZIMMER, B.; WEGENER, G. (2004), p. 172 et seq.
188 WHITE, M. K.; GOWER, S. T.; AHL, D. E. (2005), p. 28 et seq.
189 RIVELA, B. et al. (2005), p. 1 et seq.
190 ALBRECHT, S. et al.(2008), p. 15 et seq.
191 SCHEER, D. (2008), p. 6 et seq.
192 GONZÁLEZ-GARCÍA, S. et al: (2009), p. 23 et seq.
193 TUCKER, S.; SYME, M.; FOLIENTE, G: (2009), p. 2 et seq.
194 GONZÁLEZ-GARCÍA, S. et al. (2011), p. 4 et seq.

Author	**Year**	**Topic**	**Wood pro-duction**	**Trans-formation**	**Utiliz-ation**	**Recycle (material usage)**	**Dispos-al**
Energetic Usage							
JUNGBLUTH, N; FRISCHKNECHT, R.; FAIST, M.[195]	2002	LCA for energetic use of wooden products	X	X	X	-	X
RIVELA, B. et al.[196]	2006	LCA of wood wastes	X	X	X	-	X
RAYMER, A.[197]	2006	GHG emissions from different woods	X	X	X	-	-
ELTROP, L. et al.[198]	2006	LCA wood for energetic usage	-	-	X	-	-
RICHTER, K.; GUGERLI, H.[199]	1996	Comperative LCA of wood	X	X	X	-	-
EBERHARDING-ER, A. et al.[200]	2009	LCA of wood for ener-getic usage	X	X	-	-	-
SOLLI, C. et al.[201]	2009	LCA of wood based heating in Norway	X	X	X	-	-
NEUPANE, B.; HALOG, A.; DHUNGEL, S.[202]	2010	LCA for woodchip pro-duction	X	X	-	-	-
ZIMMER, B.[203]	2010	LCA for woodchip pro-duction	X	X	-	-	-
STEUBING, B.; ZAH, R.; LUDWIG, C.[204]	2011	LCA of SNG from wood heating	X	X	X	-	-
PA, A. et al.[205]	2011	LCA of wood pellet gas-ification	X	X	X	-	-
VALENTE, C.; HILLRING, B.; SOLBERG, B.[206]	2011	LCA of Norwegian wooden biomass	X	X	X	-	-

(Own illustration.)

195 JUNGBLUTH, N; FRISCHKNECHT, R.; FAIST, M. (2002), p. 5 et seq.
196 RIVELA, B. et al. (2006), p. 4 et seq.
197 PETERSEN RAYMER, A. K. (2006), p. 45 et seq.
198 ELTROP, L. et al. (2006), p. 1 et seq.
199 RICHTER, K.; GUGERLI, H. (1996), p. 2 et seq.
200 EBERHARDINGER, A. et al. (2009), p. 3 et seq.
201 SOLLI, C. et al. (2009), p. 1 et seq.
202 NEUPANE, B.; HALOG, A.; DHUNGEL, S. (2010), p. 733 et seq.
203 ZIMMER, B. (2010), p. 22 et seq.
204 STEUBING, B.; ZAH, R.; LUDWIG, C. (2011), p. 2950 et seq.
205 PA, A.; BI, X. T.; SOKHANSANJ, S. (2011), p. 6167 et seq.
206 VALENTE, C.; HILLRING, B. G.; SOLBERG, B. (2011), p. 429 et seq.

Appendix IV: Articles of LCA for SRC

Table 14:Articles of LCA for SRC

Author	**Year**	**Topic**	**Wood pro-duction**	**(Clearing)**	**Trans-formation**	**Utiliz-ation**	**Dispos-al**
RAFASCHIERI, A. et al.[207]	1999	LCA of electricity production from poplar	X	X	X	X	-
HELLER, M.; KEO-LEIAN, A.; VOLK, T.[208]	2002	LCA of energetic usage of willow cropping system	X	X	X	X	-
MURACH, D.; KNUR, L.; SCHULTZE, M.[209]	2002	LCA of heat and en-ergy production from SRC	X	X	X	X	X
ROEDL, A.[210]	2008	LCA of SRC	X	X	-	-	-
GONZÁLEZ-GARCÍA, S. et al.[211]	2009	LCA of eucalyptus plantation	X	-	-	-	-
GOGLIO, P.; OWENDE, P.[212]	2009	LCA of willow for electricity genera-tion	X	X	X	X	-
BURGER, F.[213]	2010	LCA of the combus-tion of woodchips	X	X	X	X	-
FANTOZZI, ET SEQ.; BURATTI, C.[214]	2010	LCA of biomass chains, combustion of wood chips	X	X	X	X	X
ROEDL, A.[215]	2010	LCA of energetic utilization	X	X	X	X	X
GONZÁLEZ-GARCÍA, S. et al.[216]	2012	LCA of ethanol pro-duction	X	X	X	X	-

(Own illustration.)

207 RAFASCHIERI, A.; RAPACCINI, M.; MANFRIDA, G. (1999), p. 1477 et seq.
208 HELLER, M.; KEOLEIAN, A.; VOLK, T. (2003), p. 147 et seq.
209 MURACH, D.; KNUR, L.; SCHULTZE, M. (2002), p. 1 et seq.
210 ROEDL, A. (2008), p. 1 et seq.
211 GONZÁLEZ-GARCÍA, S. et al. (2009), p. 160 et seq.
212 GOGLIO, P.; OWENDE, P. (2009), p. 389 et seq.
213 BURGER, F. (2010), S. 1 et seq.
214 FANTOZZI, F.; BURATTI, C. (2010), p. 1796 et seq.
215 ROEDL, A. (2010), p. 566 et seq.
216 GONZÁLEZ-GARCÍA, S. et al. (2012), p. 1 et seq.

Appendix V: Characteristic Values of Wood

Characteristic Values of different Types of Wood

Table 15: Characteristic values of different wood types

Type of tree	Gross density [g/cm^3] (density bd – "Darrdichte")	Modulus of elasticity [N/mm^2]	Solidity [N/mm^2]			
			Us[1] [f_t]	Bs[2] [f_m]	Cs[3] [f_c]	Ss[4] [f_v]
Spruce	0,46 (< 0,55)	11000	95	80	45	10
Willow	0,45-average (< 0,55)	7200	42-64	31-63	24-34	13-16
Poplar	0,44	8800	77	60	32	5-10
Pine	0,52	11000	100	85	47	10
[1]ultimate strength / [2]bending strength / [3]compressive strength / [4]shear strength						

(Source: modified after DEUTSCHES INSTITUT FÜR NORMUNG E.V. (Eds.) (2003), p. 2 et seq; GROSSER, D. (2005), p. 2 et seq.)

Water- and Moisture Content of Wood[217]

$$\text{Wood moisture (u)} = \frac{weight\ (water)}{\big(weight\ (moist\ wood) - \ weight\ (water)\big)}$$

$$\text{Water content (x)} = \frac{weight\ (water)}{\big(weight\ (moist\ wood)\big)}$$

$$u = \frac{x}{(1-x)}$$

$$x = \frac{u}{(1+u)}$$

Density of wood[218]

Density bd:

< 0,55 g/cm^3 = softwood

> 0,55 g/cm^3 = hardwood

[217] Cf. BAUER, C. (2007), p. 13.
[218] Cf. BAUER, C. (2007), p. 13.

Appendix VI: Ecoinvent Processes[219]

Table 16: Processes of the Ecoinvent database

Nr.	Name of the process in Ecoinvent	Source of data	Year	Geographical information
A0 Biological production of wood(chips) SRC (Elementary flows, Ecoinvent)				
3704	CO_2	-	2007	-
4054	Magnesium	-	2012	-
3958	Calcium	-	2012	-
4096	Azote	-	2012	-
4117	Potassium	-	2012	-
3635	Water	-	2012	-
3757	Forest, intensive, short cycle, resource, land	-	2012	-
3678	Oxygen	-	2012	-
A1 Diesel				
1544	diesel, burned in building machine	Sachbilanzen von Energiesystemen. Final report No. 6	2007	Swiss conditions
A2 Lube oil				
416	lubricating oil, at plant	Life Cycle Inventories of Chemicals	2007	Average Central Europenan processes
A3 Transport				
1941	transport, lorry 3.5-16t, fleet average	Life Cycle Inventories of Transport Services	2007	Swiss conditions
A4 Gravel				
463	gravel, crushed, at mine	Life Cycle Inventories of Building Products	2004	Swiss conditions
A5 Biological and technical production of conventional wood				
2516	softwood, stand establishment / tending / site development, under bark	Life Cycle Inventories of Wood as Fuel and Construction Material	2007	Data for Germany used for Central Europe
2514	softwood, allocation correction, 2	Life Cycle Inventories of Wood as Fuel and Construction Material	2007	Swiss conditions
2517	softwood, standing, under bark, in forest	Life Cycle Inventories of Wood as Fuel and Construction Material	2007	Land use data for Germany used for Central Europe

[219] Cf. SWISS CENTRE FOR LIFE CYCLE INVENTORIES (eds.) (2012), w. p.

Nr.	Name of the process in Ecoinvent	Source of data	Year	Geographical information
A6 Deposing logs				
2477	industrial wood, softwood, under bark, u=140%, at forest road	Life Cycle Inventories of Wood as Fuel and Construction Material	2007	Data for Germany used for Central Europe
A7 Production of woodchips				
2356	wood chips, softwood, u=140%, at forest	Life Cycle Inventories of Wood as Fuel and Construction Material	2007	Data for Austria used for Central Europe
A8 Transport				
1942	transport, lorry 20-28t, fleet average	Life Cycle Inventories of Transport Services	2007	Swiss conditions
A9 Herbicide				
99	herbicides, at regional storehouse	Life Cycle Inventories of Agricultural Production Systems	2007	Central European average
B1 Electricity				
761	electricity, low voltage, at grid	Sachbilanzen von Energiesystemen. Final report No. 6	2007	Swiss conditions
B2 Storage and combustion, Firing station 1000 kW				
2376	furnace, wood chips, softwood, 1000kW	Sachbilanzen von Energiesystemen. Final report No. 6	2007	Swiss conditions
B3 Disposal ashes				
2241	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	Life Cycle Inventories of Waste Treatment Services	2007	Swiss conditions
C1 Conifer Roundwood				
2495	round wood, softwood, debarked, u=70% at forest road	Life Cycle Inventories of Wood as Fuel and Construction Material	2007	Data for Germany used for Central Europe
C2 Conifer woodchips from industry				
2355	wood chips, softwood, from industry, u=40%, at plant	Life Cycle Inventories of Wood as Fuel and Construction Material	2007	Data for Austria used for Central Europe
C3 Sawdust & waste from wood industry				
2497	sawdust, Scandinavian softwood (plant-debarked), u=70%, at plant	Life Cycle Inventories of Packaging and Graphical Paper	2007	Average data from nine different sawmills, located in Sweden and Finnland
C4 Natural Gas				
1351	heat, natural gas, at industrial furnace >100kW	Sachbilanzen von Energiesystemen. Final report No. 6	2007	Extrapolation from Switzerland to Central Europe

Nr.	**Name of the process in Ecoinvent**	**Source of data**	**Year**	**Geographical information**
C5 Transport				
1944	transport, lorry >28t, fleet average	Life Cycle Inventories of Transport Services	2007	Swiss conditions
E4 Water				
2288	tap water, at user	Life Cycle Inventories of Chemicals	2004	Swiss conditions
D1 Ammoniumsulfate				
41	ammonium sulphate, as N, at regional storehouse	Life Cycle Inventories of Agricultural Production Systems	2007	Central European average
D2 Formaldehyde				
410	formaldehyde, production mix, at plant	Life Cycle Inventories of Chemicals	2007	Central European average
E1 Paraffin				
432	paraffin, at plant	Life Cycle Inventories of Detergents	2007	Data based on the Central European paraffin production

(Own illustration.)

Appendix VII: Pedigree Matrix

Table 17: Pedigree Matrix

Score / Issue	1	2	3	4	5
Reliability	Verified data based on measurement	Verified data partly based on assumptions or non-verified data based on measurements	Non verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years of difference to year of study	Less than six years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than IS years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

(modified after: WEIDEMA, P. B.; WESNAES, M. S. (1996), p. 169)

Appendix VIII: Tools to address different Types of Uncertainty

Table 18: Tools to address different types of uncertainty

	Data inaccuracy	Data gaps	Unrepresentable data	Model uncertainty	Uncertainty due to choices	Spatial variability	Temporal variability	Variability in objects	Epistemological uncertainty	Mistakes	Estimation of uncertainty
Standardisation					x					x	
Data bases		x	x								x
Data quality goals	x		x								
Data quality indicators	x		x								
Validation of data										x	
Parameter estimation		x									
Additional measurements	x	x	x					x			
Higher resolution models				x		x	x				
Critical review		x	x		x				x	x	x
Sensitivity analysis	x		x	x	x	x	x	x			
Uncertainty importance analysis	x		x	x	x	x	x	x			
Classical statistical analysis	x					x	x	x			
Bayesian statistical analysis	x										
Interval arithmetic	x										
Vague error intervals	x										
Probabilistic simulation	x							x			
Scenario modelling			x	x	x	x	x	x			
Rules of thumb	x										

(according to: BJOERKLUND, A. E. (2002), p. 70)

Appendix IX: Pedigree Matrix of the present Study

Table 19: Pedigree matrix of the present study

<table>
<tr><th rowspan="4">Indicator</th><th rowspan="4">Score</th><th>Production conventional wood- (chips)</th></tr>
<tr><th>Production wood- (chips) from SRC</th></tr>
<tr><th>Combustion of woodchips</th></tr>
<tr><th>Production particleboard</th></tr>
<tr><td></td><td></td><td></td></tr>
<tr><th>Issue</th><th>Score</th><th>Description</th></tr>
<tr><td rowspan="4">Reliability</td><td>2</td><td>The production of conventional wood-(chips) is modeled with the Ecoinvent database. Data of this database is validated but partially based on assumptions.[220]</td></tr>
<tr><td>3</td><td>The production of wood-(chips) was assessed with data of three different studies. Data of the biological and technical production from ROEDL, A. (2008) is based on on-site measurements and assumptions for the biological production. Data for herbicides from RÖHRICHT, C.; RUSCHER, K. (2009) and data of BOELKE, B. (2006) was gathered with on-site measurements. Data for lube oil from GOGLIO, P.; OWENDE, P. (2009) is based on different studies and assumptions.[221] The present study assumes that poplar wood can be substituted with willow. The used data from the studies could not be verified from the author. Additionally processes of Ecoinvent were used which are validated.</td></tr>
<tr><td>2</td><td>Data for the combustion is computed with Ecoinvent. Data in Ecoinvent was gathered with literature and by personal communication. Data is validated. It is assumed that there is an equal combustion for both woods.</td></tr>
<tr><td>3</td><td>Data for the production of the particleboard was calculated with the studies of RIVELA, B. et al. (2005) and WILCZYNSKI, A. et al. (2011).[222] Additionally processes of Ecoinvent were used. RIVELA, B. et al. (2005) gathered data by on-site measurements and assumptions. Due to variability of the moisture contents of the multiple raw materials, the usage of thermal energy for the drying process was estimated.[223] Data of WILCZYNSKI, A. et al. (2011) was gathered by on-site measurement.[224] The present study assumes that pine wood can be substituted with spruce, energy from cogeneration can be substituted with energy from gas and that the same inputs on energy and lubricants existing for an interior layer from wood from SRC. Data is not verified by the author.</td></tr>
<tr><td rowspan="4">Completeness</td><td>2</td><td>Due to data of Ecoinvent is validated, it is assumed, that a suitable time interval is present. Data was examined for a small sample in Germany.</td></tr>
<tr><td>2</td><td>Data for each process was gathered at one site. The time period is suitable and includes multiple growing periods each. The used data of Ecoinvent is validated. Thus, it is assumed, that suitable time intervals and samples were considered.</td></tr>
<tr><td>1</td><td>The time period amounts one year and is assumed as suitable. Due to multiple sources of literature, samples cannot be tracked but are assumed as suitable due to a validation process for data of Ecoinvent.[225]</td></tr>
<tr><td>4</td><td>Data is representative for the production of a particleboard. It was gathered from one sample. There is a short time interval. Data was gathered for one production line. Data originates from two different factories. The used data of Ecoinvent is validated. Thus, it is assumed, that suitable time intervals and samples were considered.</td></tr>
</table>

[220] Cf. SWISS CENTRE FOR LIFE CYCLE INVENTORIES (eds.) (2012), w.p.
[221] Cf. ROEDL, A. (2008), p. 1.; RÖHRICHT, C.; RUSCHER, K. (2009), p. 23.; GOGLIO, P.; OWENDE, P. (2009), p. 391.
[222] Cf. RIVELA, B. et al. (2005), p. 106; Cf. WILCZYNSKI, A. et al. (2011), p. 194.
[223] Cf. RIVELA, B. et al. (2005), p.110.
[224] Cf. WILCZYNSKI, A. et al. (2011), p. 168 et seq.
[225] Cf. SWISS CENTRE FOR LIFE CYCLE INVENTORIES (eds.) (2012), w.p.

Indicator	Score	Description
		Production conventional wood- (chips)
		Production wood- (chips) from SRC
		Combustion of woodchips
		Production particleboard
Issue	**Score**	**Description**
Temporal corre-lation	2	According to Swiss Centre for Life Cycle Inventories data for the conventional wood production was gathered in the year 2007.
	2	Data for the biological and technical production was gathered 2008; for herbi-cides, land use and lube oil 2007 according to Swiss Centre for Life Cycle Inven-tories.
	2	According to Swiss Centre for Life Cycle Inventories data for the combustion was gathered in year 2007.
	3	Data from RIVELA, B. et al. (2005) was gathered in 2006; from WILCZYNSKI, A. et al. (2011) in 2011.[226] Data of Ecoinvent was gathered in year 2007.
Geo-Graphical correlation	1	Data was gathered in Germany and is valid for Central Europe.
	3	Data for the biological and technical production and the production of herbicides was gathered in Germany, for herbicides in Ireland. The production of woodchips from SRC shall be adaptable for Central Europe.
	1	Data was evaluated under swiss conditions.
	1	Data from RIVELA, B. et al. (2005) was gathered in a Spanish -; from WILCZYNSKI, A. et al. (2011) in a Polish particleboard factory.[227] Due to equal working processes for the particleboard factories in Europe, the best rating is giv-en. Moreover, the chosen factory is representative for the state of the art.[228] ,Data of Ecoinvent is valid for Central European conditions.
Tech-nological correlation	1	Data was gathered for processes and materials under study.
	4	Data was gathered on related processes and materials but same technology. In the present study it is assumed that willow can be substituted with poplar.
	4	Data was gathered for processes and materials under study for combustion of conventional wood but not for SRC.
	4	Data was gathered on related processes and materials but same technology. In the present study it is assumed that pine can be substituted with spruce.

(Own illustration.)

Appendix X: Data of LCIA for Energy and Particleboard Production

Table 20: Production of woodchips from conventional forestry, Characterization, CML

	EP	POCP	GWP	AP
Diesel	6,90738E-07	3,7595E-07	0,000324196	2,49348E-06
Gravel	2,75E-08	8,25E-09	1,19E-05	7,07E-08
Transport	3,03E-08	1,41E-08	2,33E-05	1,15E-07
Lube oil	6,35E-11	8,29E-11	1,79E-08	1,61E-10
Wood	0	0	-0,102018946	0

(Own illustration.)

226 Cf. RIVELA, B. et al. (2005), p. 106; Cf. WILCZYNSKI, A. et al. (2011), p. 194.
227 Cf. RIVELA, B. et al. (2005), p. 106; Cf. WILCZYNSKI, A. et al. (2011), p. 194.
228 Cf. RIVELA, B. et al. (2005), p. 107.

Table 21: Production of woodchips from SRC, Characterization CML

	EP	POCP	GWP	AP
Diesel	1,01E-06	5,46E-07	0,000474277	3,65E-06
Herbicide	9,79E-08	3,00E-08	3,23E-05	4,02E-07
Lube oil	1,63E-08	2,13E-08	4,60E-06	4,13E-08
Wood	0	0	-0,1042875	0

(Own illustration.)

Table 22: Comparison of woodchips from conventional forestry and SRC, Normalization, CML

	EP	POCP	GWP	AP
SRC	8,74E-17	7,24E-17	-2,12E-14	1,49E-16
Forest	5,83E-17	5,20E-19	-2,08E-14	9,79E-17

(Own illustration.)

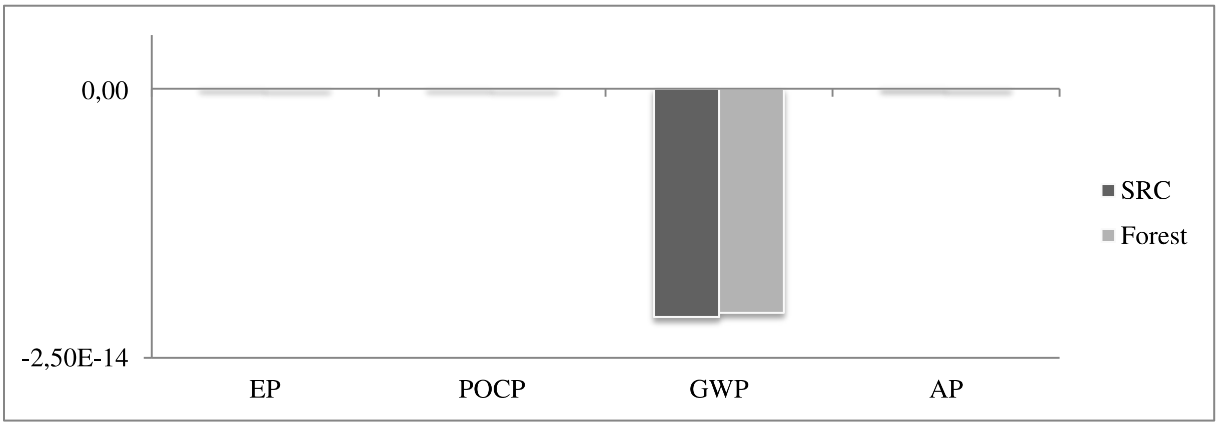

Figure 46: Impact assessment woodchips, Normalization, CML
(Own illustration.)

Table 23: Combustion of woodchips, Characterization, CML

	Transport	Disposal	Combustion	Power-grid
EP	1,86E-06	1,56E-07	1,47E-05	1,23E-05
POCP	9,03E-07	8,79E-09	5,18E-06	4,24E-07
GWP	1,18E-03	9,63E-06	0,1026954	0,002993774
AP	6,70E-06	6,58E-07	5,42E-05	4,58E-06

(Own illustration.)

Table 24: Combustion of woodchips, Normalization, CML

	Total
EP	2,26E-15
POCP	7,90E-16
GWP	2,19E-14
AP	2,42E-15

(Own illustration.)

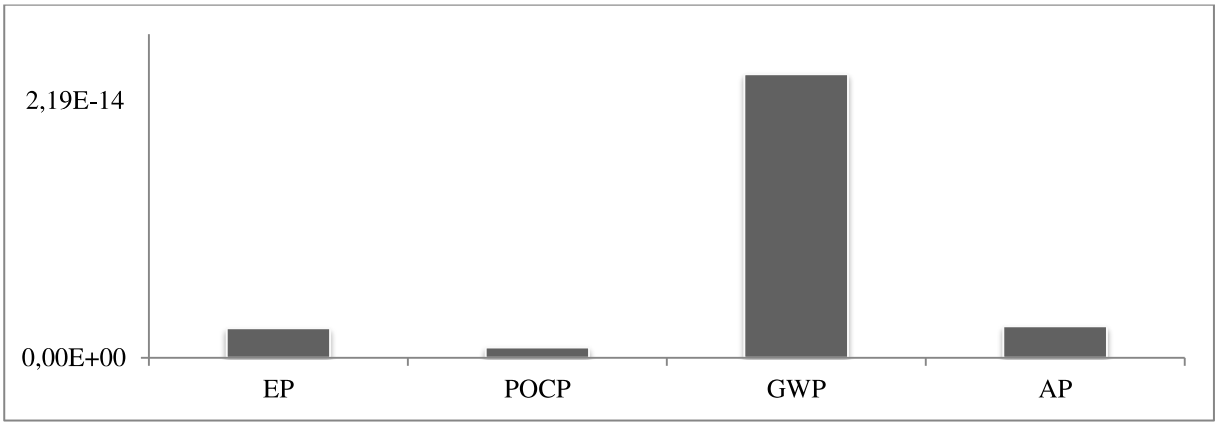

Figure 47: Impact assessment combustion of woodchips, Normalization, CML (Own illustration.)

Table 25: Production of woodchips from conventional forestry, Characterization, EI99

	Diesel	**Gravel**	**Transport**	**Lube oil**	**Wood**
HH, Carcinogens [DALY]	1,25E-11	4,64E-12	7,81E-14	5,66E-15	0
HH, Climate change [DALY]	6,79E-11	2,49E-12	4,89E-12	3,70E-15	-2,1424E-08
HH, Ozone depletion [DALY]	4,60E-14	1,34E-15	0	1,15E-17	0
HH, Respiratory (anor.) [DALY]	6,27E-10	1,53E-11	2,81E-11	1,56E-14	0
HH, Respiratory (or.) [DALY]	5,66E-13	2,87E-14	1,56E-14	1,98E-16	0
HH, Radiation [DALY]	2,05E-13	3,80E-13	0	9,06E-17	0
EQ, Land use [PDF*m2*a]	5,74E-07	1,07E-06	0	1,84E-10	0,00502806
EQ, Land modification [PDF*m2*a]	2,85E-06	-3,31E-07	0	7,31E-10	7,6813E-05
EQ, Ecotoxicity [PDF*m2*a]	2,61E-06	7,68E-07	7,27E-07	6,06E-10	0
EQ, Acidification, Eutrophication [PDF*m2*a]	2,22E-05	4,47E-07	1,31E-06	4,02E-10	0
R, Ressources, Minerals [MJ surplus energy]	2,26E-06	1,20E-06	0	7,16E-10	0

(Own illustration.)

Table 26: Production of woodchips from SRC, Characterization, EI99

	Diesel	**Herbicide**	**Lube oil**	**Wood**
HH, Carcinogens [DALY]	1,77E-11	1,10E-11	1,46E-12	0
HH, Climate change [DALY]	9,94E-11	6,66E-12	9,52E-13	-2,19E-08
HH, Ozone depletion [DALY]	6,18E-14	1,61E-13	2,96E-15	0
HH, Respiratory (anor.) [DALY]	9,25E-10	3,08E-11	4,02E-12	0
HH, Respiratory (or.) [DALY]	8,15E-13	2,38E-11	5,09E-14	0
HH, Radiation [DALY]	2,88E-13	2,24E-13	2,33E-14	0
EQ, Land use [PDF*m2*a]	7,97E-07	2,08E-07	4,74E-08	0
EQ, Land modification [PDF*m2*a]	3,98E-06	7,03E-08	1,88E-07	0,0646875
EQ, Ecotoxicity [PDF*m2*a]	3,75E-06	1,10E-06	1,56E-07	0
EQ, Acidification, Eutrophication [PDF*m2*a]	3,27E-05	8,55E-07	1,04E-07	0
R, Ressources, Minerals [MJ surplus energy]	3,31E-06	1,44E-06	1,84E-07	0

(Own illustration.)

Table 27: Comparison of woodchips from conventional forestry and SRC, Normalization, EI99

	HH	**EQ**	**R**
SRC	-8,63248E-06	1,6474E-05	3,3358E-08
Forest	-8,83026E-06	1,36237E-06	2,3387E-08

(Own illustration.)

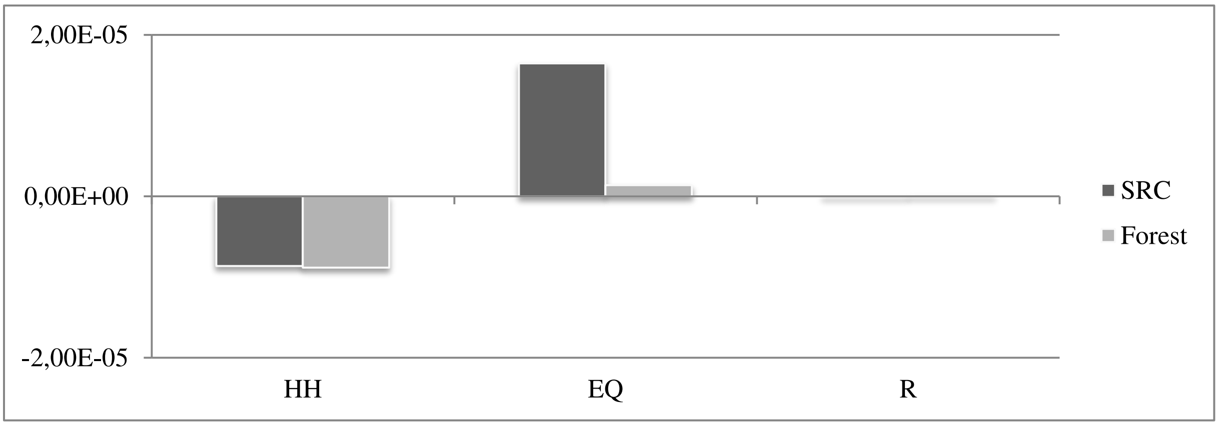

Figure 48: Impact assessment woodchips, Normalization, EI99

(Own illustration.)

Table 28: Combustion woodchips, Characterization, EI99

	Disposal	**Combustion**	**Grid**	**Transport**
HH, Carcinogens [DALY]	3,45E-07	6,57E-08	6,79E-07	1,41E-08
HH, Climate change [DALY]	8,02E-10	9,03E-06	2,61E-07	1,03E-07
HH, Ozone depletion [DALY]	7,87E-12	0	5,48E-10	8,54E-10
HH, Respiratory (anor.) [DALY]	9,08E-10	5,13E-06	7,97E-08	1,25E-07
HH, Respiratory (or.) [DALY]	2,40E-10	1,34E-07	3,10E-08	1,82E-08
HH, Radiation [DALY]	9,97E-10	0	1,06E-06	1,74E-08
EQ, Land use [PDF*m2*a]	3,85E-10	0	3,41E-09	4,01E-10
EQ, Land modification [PDF*m2*a]	-4,70E-10	0	5,37E-10	1,87E-09
EQ, Ecotoxicity [PDF*m2*a]	3,64E-08	1,27E-06	1,41E-07	3,37E-08
EQ, Acidification, Eutrophication [PDF*m2*a]	8,52E-10	1,56E-06	4,96E-08	1,71E-07
R, Ressources, Minerals [MJ surplus energy]	1,19E-09	0	5,31E-07	8,76E-09

(Own illustration.)

Table 29: Combustion of woodchips, Normalization, EI99

	Total
HH	8,27E-06
EQ	4,62E-06
R	5,65E-07

(Own illustration.)

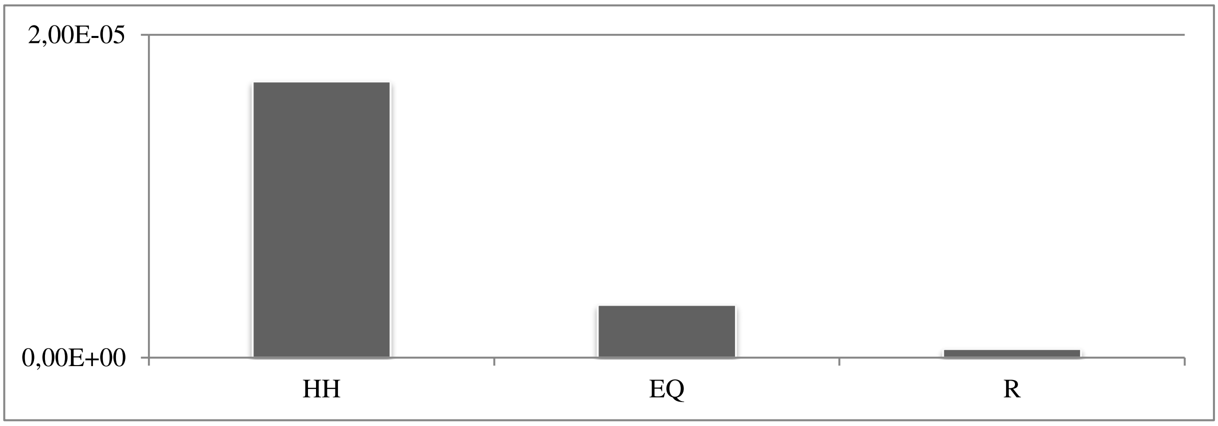

Figure 49: Impact assessment combustion of woodchips, Normalization, EI99

(Own illustration.)

Table 30: Manufacturing particleboard, SRC, Characterization, selected values, CML

	Exterior layer	**Interior layer**	**Grid (BS)**	**Ammoni-umchlorid**	**Formalde-hyde**	**Water**	**Grid (BF)**
Eutrophication potential (EP) [kg Phosphat-Äqv.]	7,28E-02	1,26E-01	3,09E-02	2,46E-03	7,88E-02	1,75E-05	1,55E-01
Photo-oxidant creation potential (POCP) [kg Ethen-Äqv.]	1,92E-02	4,47E-02	1,07E-03	2,47E-04	3,19E-02	2,78E-06	5,33E-03
Global warming potential (GWP) [kg CO2-Äqv.]	-4,88E+02	-1,78E+03	7,54E+00	7,77E-01	7,51E+01	6,12E-03	3,77E+01
Acidification potential (AP) [kg SO2-Äqv.]	1,11E-01	2,58E-01	1,15E-02	3,02E-03	1,68E-01	2,97E-05	5,77E-02
Fossil Ressource [kg Sb-Äqv.]	2,0E-05	1,1E-04	9,7E-06	1,2E-05	2,8E-04	5,2E-09	4,9E-05

(Own illustration.)

Table 31: Manufacturing particleboard, conventional wood, Characterization, selected values, CML

	Exterior layer	**Interior layer**	**Grid (BS)**	**Ammoni-umchlorid**	**Formal-dehyde**	**Paraffin**	**Water**	**Grid (BF)**
Eutrophication potential (EP) [kg Phosphat-Äqv.]	7,3E-02	1,4E-01	3,1E-02	2,0E-03	7,9E-02	1,8E-03	1,7E-05	1,5E-01
Photo-oxidant creation potential (POCP) [kg Ethen-Äqv.]	1,9E-02	5,5E-02	1,1E-03	7,6E-04	3,2E-02	1,3E-03	2,8E-06	5,3E-03
Global warming potential (GWP) [kg CO2-Äqv.]	-4,9E+02	-1,0E+03	7,5E+00	2,0E+00	7,5E+01	1,8E+00	6,1E-03	3,8E+01
Acidification potential (AP) [kg SO2-Äqv.]	1,1E-01	3,1E-01	1,2E-02	6,4E-03	1,7E-01	1,1E-02	3,0E-05	5,8E-02
Fossil Ressource [kg Sb-Äqv.]	7,3E-02	1,4E-01	3,1E-02	2,0E-03	7,9E-02	1,8E-03	1,7E-05	1,5E-01

(Own illustration.)

Table 32: Comparison manufacturing particleboard, Normalization, CML

	ADP f.	**EP**	**POCP**	**GWP**	**AP**
SRC	2,4E-10	3,6E-11	1,2E-11	-4,4E-10	2,2E-11
Forest	2,5E-10	3,8E-11	1,4E-11	-2,9E-10	2,5E-11

(Own illustration.)

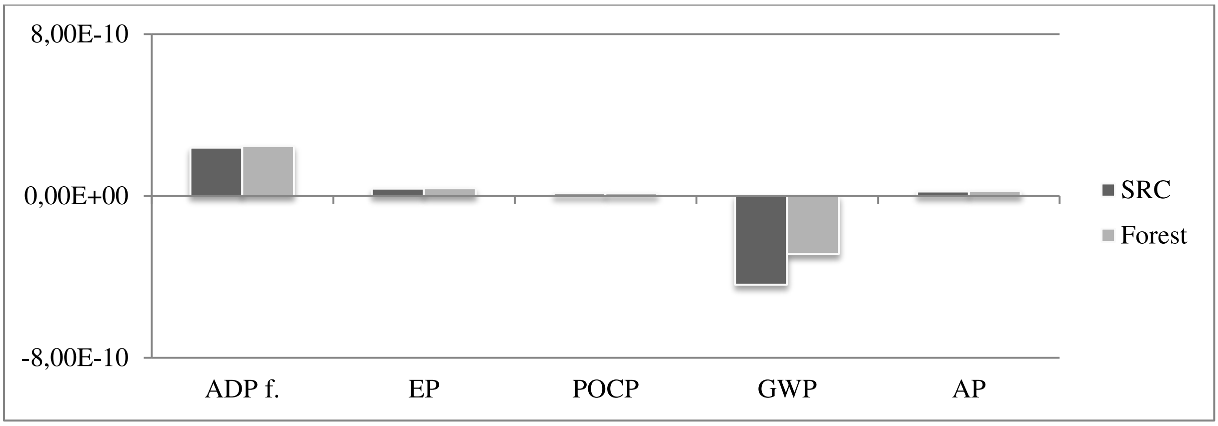

Figure 50: Impact assessment particleboard, Normalization, CML
(Own illustration.)

Table 33: Manufacturing particleboard, SRC, Characterization, selected values, EI99

	Exterior layer	**Interior layer**	**Grid (BS)**	**Ammonium-chlorid**	**Formaldehyde**	**Water**	**Grid (BF)**
HH, Carcinogens [DALY]	6,8E-06	1,0E-05	3,4E-06	3,2E-07	1,7E-05	2,8E-09	1,7E-05
HH, Climate change [DALY]	-1,0E-04	-3,7E-04	1,6E-06	1,6E-07	1,5E-05	1,3E-09	7,9E-06
HH, Ozone depletion [DALY]	1,1E-08	2,5E-08	3,0E-10	7,8E-11	1,2E-08	3,1E-13	1,5E-09
HH, Respiratory (anor.) [DALY]	1,8E-05	4,4E-05	2,1E-06	4,0E-07	2,4E-05	4,4E-09	1,1E-05
HH, Respiratory (or.) [DALY]	4,1E-08	5,4E-07	5,3E-09	5,8E-10	6,8E-08	2,1E-11	2,7E-08
HH, Radiation [DALY]	1,4E-07	2,1E-07	7,1E-08	4,5E-09	2,1E-07	8,2E-11	3,6E-07
EQ, Land use [PDF*m2*a]	7,8E+00	1,5E-01	3,4E-02	6,4E-03	4,0E-01	3,0E-04	1,7E-01
EQ, Land modification [PDF*m2*a]	3,6E-01	1,2E+03	5,3E-03	2,6E-03	4,5E-01	-1,7E-05	2,7E-02
EQ, Ecotoxicity [PDF*m2*a]	7,1E-01	1,1E+00	2,9E-01	3,9E-02	1,6E+00	2,0E-04	1,4E+00
EQ, Acidification, Eutrophication [PDF*m2*a]	6,9E-01	1,7E+00	4,7E-02	1,2E-02	8,3E-01	9,0E-05	2,3E-01
R, Ressources, Minerals [MJ surplus energy]	4,1E-01	7,3E-01	2,0E-01	5,6E-02	2,9E+00	1,5E-04	9,9E-01

(Own illustration.)

Table 34: Production particleeboard, conventional wood, Characterization, selected values, EI99

	Exterior layer	**Interior layer**	**Grid (BS)**	**Ammoni-umchlo-rid**	**Formal-dehyde**	**Paraffin**	**Water**	**Grid (BF)**
HH, Car-cinogens [DALY]	6,8E-06	1,1E-05	3,4E-06	6,3E-07	1,7E-05	3,8E-07	2,8E-09	1,7E-05
HH, Cli-mate change [DALY]	-1,0E-04	-2,2E-04	1,6E-06	4,1E-07	1,5E-05	3,7E-07	1,3E-09	7,9E-06
HH, Ozo-ne deple-tion [DA-LY]	1,1E-08	2,3E-08	3,0E-10	2,2E-10	1,2E-08	1,3E-10	3,1E-13	1,5E-09
HH, Re-spiratory (anor.) [DALY]	1,8E-05	5,8E-05	2,1E-06	9,9E-07	2,4E-05	1,3E-06	4,4E-09	1,1E-05
HH, Re-spiratory (or.) [DALY]	4,1E-08	1,1E-07	5,3E-09	1,5E-09	6,8E-08	2,3E-09	2,1E-11	2,7E-08
HH, Radi-ation [DALY]	1,4E-07	2,3E-07	7,1E-08	3,9E-09	2,1E-07	1,9E-09	8,2E-11	3,6E-07
EQ, Land use [PDF*m2 *a]	7,8E+00	1,9E+02	3,4E-02	1,5E-02	4,0E-01	8,8E-03	3,0E-04	1,7E-01
EQ, Land modifica-tion [PDF*m2 *a]	3,6E-01	3,5E+00	5,3E-03	6,7E-03	4,5E-01	5,2E-03	-1,7E-05	2,7E-02
EQ, Eco-toxicity [PDF*m2 *a]	7,1E-01	1,2E+00	2,9E-01	8,2E-02	1,6E+00	6,3E-02	2,0E-04	1,4E+00
EQ, Acid-ification, Eutrophi-cation [PDF*m2 *a]	6,9E-01	2,2E+00	4,7E-02	2,1E-02	8,3E-01	4,1E-02	9,0E-05	2,3E-01
R, Ressource s, Miner-als [MJ surplus energy]	4,1E-01	8,1E-01	2,0E-01	1,3E-01	2,9E+00	8,0E-02	1,5E-04	9,9E-01

(Own illustration.)

Table 35: Comparison manufacturing particleboard, Normalization, EI99

	HH	EQ	R
SRC	-1,0E-01	3,3E-01	3,6E-02
Forest	-4,3E-02	6,8E-02	3,8E-02

(Own illustration.)

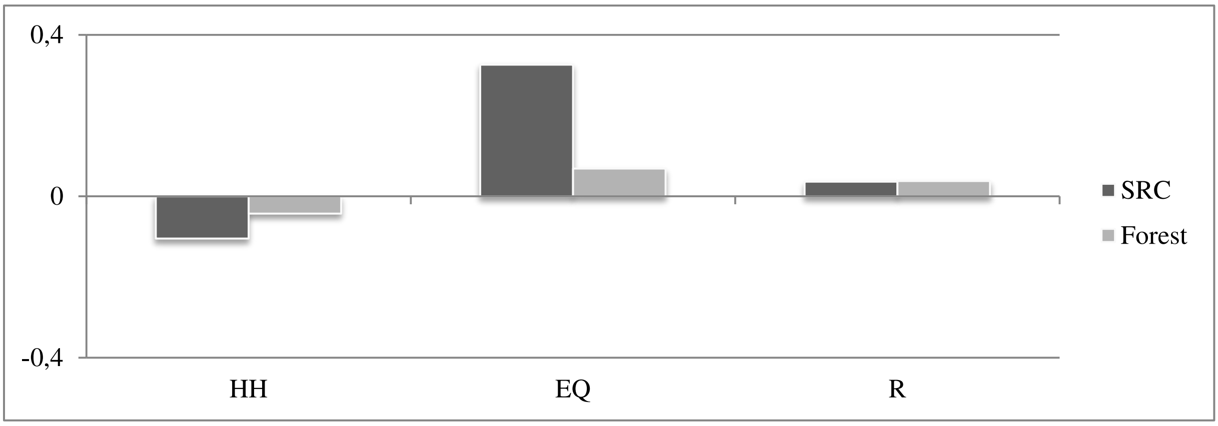

Figure 51: Impact assessment particleboard, Normalization, EI99
(Own illustration.)

Appendix XI: Calculations for LCI

Table 36: Production of woodchips from conventional forestry

Water content (x)	x = u/ (1+u) x = 120%/ (100% + 120%) x = 54%
Weight per m^3 - with a gross density of 0,46g/ cm^3 (i) [229]	i = 155 kg/ m^3
Weight of 3,33*E-4 m^3 of woodchips, bd (y)	y = 3,33*E-4 m^3 * i y = 0,051 kg
Weight of 3,33*E-4 m^3 of woodchips with water content of 54% (z)	z = y * 100% / 46% z = 0,11 kg

(Own illustration.)

[229] Cf. AUSTRIAN STANDARDS INSTITUTE (eds.) (1998), p. 3 et seq.

Table 37: Production of woodchips from SRC

Weight per m^3 (bd) - with a gross density of 0,45g/ cm^3 (ii) [230]	ii	=	155 kg/ m^3
Volume of 1000 kg (bd) woodchips (b)	b b	= =	1000 kg * $1m^3$ / 155 kg 6,45 m^3
Weight of 3,33*E-4 m^3 of woodchips, bd (c)	c c	= =	3,33*E-4 m^3 * 1000 kg / 6,45 m^3 0,051 kg/ m^3
Weight of Calcium per ton (e)	e e	= =	1t * 54 kg / 10t 5,4 kg
Weight of Magnesium per ton (f)	f f	= =	1t * 8 kg / 10t 0,8 kg
Weight of Azote per ton (g)	g g	= =	1t * 37 kg / 10t 3,7 kg
Weight of phosphor per ton (h)	h h	= =	1t * 37 kg / 10t 3,7 kg
Weight of Potassium per ton (k)	k k	= =	1t * 6 kg / 10t 0,6 kg
Land use for 1 ton of woodchips (m) (10t / ha /a)	m m	= =	1t * 10000 m^2 / 10t 1000 m^2
Lube oil for 1 ton of woodchips (n)	n	=	1,56 kg * 1t / 10t
Herbicide for 1 ton of woodchips (o)	o	=	0,7 kg * 1t / 10t
Further calculations for functional units were calculated by the Gabi software, with the assumption that there is a weight of 1000 kg for 6,45 m^3 (bd).			

(Own illustration.)

Table 38: Combustion of woodchips

Transport from wood production area to firing system in tkm (a)	a a	= =	z, (c) * 30 km 0,0033 tkm

(Own illustration.)

Table 39: Wood preperation subsystem for particleboard

Volume of 166,15 kg woodchips with humidity of 40% (water content = 28,5%) (xx)	xx xx	= =	166,15 kg / (i * 100/71,5) 0,77 m^3
Volume of 892,82 kg round wood with humidity of 70% (water content = 41%; average weight of 430 kg/ m^3 (bd)[231]) (yy)	yy yy	= =	892,82 kg/ (430 kg * 100/59) 1,22 m^3
Volume of 203,35 kg sawdust with humidity of 70% (water content = 41%; average weight of 168 kg/ m^3 (bd)[232]) (zz)	zz zz	= =	203,35 kg/ (168 kg * 100/59) 0,71 m^3

(Own illustration.)

[230] Cf. AUSTRIAN STANDARDS INSTITUTE (eds.) (1998), p. 3 et seq.
[231] GESAMTVERBAND DEUTSCHER HOLZHANDEL (eds.) (2012), w.p.
[232] Cf. VOGEL, K. (1999), p. 11 et seq.

Appendix XII: Survey of the interior Layer from conventional Wood

Table 40: Interior layer conventional wood, CML,

Indica-tor	Total	IWC*	Power-Grid	Natural Gas	Trans-port	Round Wood				
						Gravel	Diesel	Transpo rt	Lube Oil	Wood
ADP f.	1,1E+1	11,06	7,4E+01	6,3E+02	1,1E+02	5,4E+00	2,0E+02	0,0E+00	2,2E+00	0,0E+00
%	1	1	7	61	11	1	20	0	0	0
EP	2,1E-03	0,00	2,8E-02	5,4E-03	1,1E-02	1,0E-03	3,1E-02	1,1E-03	1,1E-04	0,0E+00
%	3	3	35	7	14	1	39	1	0	0
POCP	2,9E-03	0,00	9,8E-04	7,0E-03	5,4E-03	3,0E-04	1,7E-02	5,2E-04	1,5E-04	0,0E+00
%	9	9	3	20	16	1	49	2	0	0
GWP	-2,3E+02	-234,67	6,9E+00	4,0E+01	7,3E+00	4,4E-01	1,5E+01	8,5E-01	3,2E-02	-1,0E+03
%	20,24	-20,24	0,60	3,46	0,63	0,04	1	0,07	0,00	-85,84
AP	5,0E-03	0,00	1,1E-02	3,1E-02	4,0E-02	2,6E-03	1,1E-01	4,2E-03	2,9E-04	0,0E+00
%	2,42	2,42	5,13	14,95	19,46	1,25	55	2,04	0,14	0,00
* Industrial woodchips										

(Own illustration.)

Table 41: Interior layer conventional wood, EI99

	Total	IWC*	Power-Grid	Natural Gas	Transport	Round Wood				
						Gravel	Diesel	Transport	Lube Oil	Wood
HH	-7,0E-02	-2,0E-02	1,3E-02	1,7E-02	1,7E-03	7,1E-04	5,0E-03	1,8E-04	2,2E-05	-8,7E-02
%		-29	18	24	2	1	7	0	0	-124
EQ	5,6E-02	1,2E-03	1,2E-03	1,9E-03	1,2E-03	8,5E-05	2,9E-03	1,6E-04	3,7E-06	4,7E-02
%		2	2	3	2	0	5	0	0	85
R	5,5E-03	1,6E-04	3,2E-03	1,1E-03	6,1E-05	3,0E-04	6,9E-04	0,0E+00	8,6E-06	0,0E+00
%		3	58	19	1	5	13	0	0	0

* Industrial woodchips

(Own illustration.)

Table 42: Evaluating paraffin, conventional wood, EI99

	Power	Ammon.	UF -Resin	Water	Paraffin
HH	0,19	0,13	2,94	0,00015	0,079
%	5,91%	3,95%	87,76%	0,00%	2,37%
EQ	3,42E-06	6,34E-07	1,67E-05	2,77E-09	3,84E-07
%	16%	3%	79%	0%	2%
R	0,372	0,121	3,241	0,00056	0,117
%	9,67%	3,23%	84,04%	0,01%	3,04%

(Own illustration.)

Appendix XIII: Sensitivity Analysis

Scenario 1

Table 43: Reduction of diesel consumption,conventional wood, Characterization, CML

	Total
(EP) [kg Phosphat-Äqv.]	6,81E-07
(POCP) [kg Ethen-Äqv.]	3,62E-07
(GWP) [kg CO2-Äqv.]	-0,1016912
(AP) [kg SO2-Äqv.]	2,44E-06

(Own illustration.)

Table 44: Reduction of diesel consumption, SRC, Characterization, CML

	Total
(EP) [kg Phosphat-Äqv.]	1,01E-06
(POCP) [kg Ethen-Äqv.]	5,4221E-07
(GWP) [kg CO2-Äqv.]	-0,103
(AP) [kg SO2-Äqv.]	3,70E-06

(Own illustration.)

Table 45: Reduction of diesel consumption conventional wood, Characterization, EI99

	Total
HH [DALY]	-2,07E-08
EQ [PDF*m2*a]	0,005
R [MJ surplus energy]	3,24E-06

(Own illustration.)

Table 46: Reduction of diesel consumption SRC, Characterization, EI99

	Total
HH [DALY]	-2,09E-08
EQ [PDF*m2*a]	6,47E-02
R [MJ surplus energy]	4,61E-06

(Own illustration.)

Scenraio 2

Table 47: Increasing transport distance, conventional wood, Characterization, CML

	Total
(EP) [kg Phosphat-Äqv.]	3,0619E-05
(POCP) [kg Ethen-Äqv.]	7,3159E-06
(GWP) [kg CO2-Äqv.]	0,0057
(AP) [kg SO2-Äqv.]	7,1852E-05

(Own illustration.)

Table 48: Increasing transport distance, conventional wood, Characterization, EI99

	Total
HH [DALY]	6,19E-08
EQ [PDF*m2*a]	7,07E-03
R [MJ surplus energy]	8,41E-05

(Own illustration.)

Scenario 3

Table 49: Particleboard with wood firing system, conventional wood, Characterization, CML

	Total
(ADP f.) [MJ]	5111,225
(EP) [kg Phosphat-Äqv.]	0,527
(POCP) [kg Ethen-Äqv.]	0,101
(GWP) [kg CO2-Äqv.]	-1555,215
(AP) [kg SO2-Äqv.]	0,704

(Own illustration.)

Table 50: Particleboard with wood firing system, SRC, Characterization, CML

	Total
(ADP f.) [MJ]	5111,225
(EP) [kg Phosphat-Äqv.]	0,527
(POCP) [kg Ethen-Äqv.]	0,101
(GWP) [kg CO2-Äqv.]	-1555,215
(AP) [kg SO2-Äqv.]	0,704

(Own illustration.)

Table 51: Particleboard with wood firing system, conventional wood, Characterization, EI99

	Total
HH [DALY]	-3,42851E-05
EQ [PDF*m2*a]	225,859
R [MJ surplus energy]	5,582

(Own illustration.)

Table 52: Particleboard with wood firing system, SRC, Characterization, EI99

	Total
HH [DALY]	-2,06E-04
EQ [PDF*m2*a]	1251,055
R [MJ surplus energy]	5,343

(Own illustration.)

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Abstract

Worldwide there is an increasing demand of natural resources. In future, non-renewable resources get substituted by renewable resources in the energetic sector as well as in the material sector. That implies a stronger usage of renewable resources especially - wood.[233] In 2009 there was a usage of 77 million cubic meters of wood for material applications and a quantity of 55 million cubic meters for energetic applications in Germany alone. Furthermore, there is an increasing demand on wood for energetic purposes. In 2007 this problematic development led to the first supply bottlenecks. [234] To meet the increasing demands of the future, Short Rotation Coppices (SRC) can help to improve the wood provision.

An SRC is a planting of fast growing coppice on agricultural areas, which is managed more intensively than usual forestry practices for a quicker production of wooden biomass.[235] With a comparative LCA of conventional wood and wood from SRC the present study evaluates if wood from SRC is reasonable to cover the increasing demand of wood for material and energetic purposes in an environmental friendly way. A comprehensive literature research regarding LCAs of wood and wooden products shows that there are no previous studies comparing the two types of wood. Hence, the present study examines a particleboard production as the material scenario and the combustion of woodchips in a firing system as the energetic scenario to compare the ecological advantages and disadvantages of wood from SRC and conventional wood. The LCA is implemented with the Gabi software designed by PE International.[236] Data is obtained from previous LCA studies evaluating the production of wood, the particleboard production and the combustion of wood.

Additionally, data from the Ecoinvent database is used.[237] Functional units are the production of $1m^3$ particleboard and the production of 1 MJ of thermal energy. The LCIA is implemented with the “Ecoindicator” as endpoint- and “CML 2001” as midpoint approach to cover broad range of environmental issues. Moreover a sensitivity analyses shows the impact of decisive variables on the results of “Ecoindicator” and “CML 2001”.

Results reveal that outcomes of the LCIA are dependent of the assessment method and the processed part of trees from conventional forestry. The present study shows, that with an efficient land use, wood from SRC can help to cover the increasing demand of wood for material and energetic purposes in a sustainable way. However, an immediate usage of wood for energetic purposes has to be seen critical. Instead, a cascaded and sustainable utilization of wood is recommendable to counteract climate change and to improve the efficient use of the renewable resource - “wood”.

Keywords: Comparative LCA, wood, short rotation coppice, conventional forestry, ecoindicator, CML 2001, particleboard, thermal energy

233 Cf. BMELV (eds.) (2004), p. 9 et seq.
234 Cf. BMELV (eds.) (2009), p. 5 et seq.
235 Cf. ROEHRICHT, C.; RUSCHER, K. (2009), p. 4.
236 Cf. PE INTERNATIONAL (eds.) (2012), w. p.
237 Cf. SWISS CENTRE FOR LIFE CYCLE INVENTORIES (eds.) (2012), w. p.

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